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A Ricardian Analysis of the Impact of Climate Change on African Cropland

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Abstract

This study examines the impact of climate change on cropland in Africa. It is based on a survey of more than 9,000 farmers in 11 countries: Burkina Faso, Cameroon, Egypt, Ethiopia, Ghana, Kenya, Niger, Senegal, South Africa, Zambia, and Zimbabwe. The study uses a Ricardian cross-sectional approach in which net revenue is regressed on climate, water flow, soil, and economic variables. The results show that net revenues fall as precipitation falls or as temperatures warm across all the surveyed farms.

In addition to examining all farms together, the study examined dryland and irrigated farms separately. Dryland farms are especially climate sensitive. Irrigated farms have a positive immediate response to warming because they are located in relatively cool parts of Africa. The study also examined some simple climate scenarios to see how Africa would respond to climate change. These uniform scenarios assume that only one aspect of climate changes and the change is uniform across all of Africa. In addition, the study examined three climate change scenarios from Atmospheric Oceanic General Circulation Models. These scenarios predicted changes in climate in each country over time.

Not all countries are equally vulnerable to climate change. First, the climate scenarios predict different temperature and precipitation changes in each country. Second, it is also important whether a country is already hot and dry. Third, the extent to which farms are irrigated is also important.

This paper—a product of the Sustainable Rural and Urban Development Team, Development Research Group—is part of a larger effort in the group to mainstream climate change research. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at robert.mendelsohn@yale.edu.

A RICARDIAN ANALYSIS OF THE IMPACT OF CLIMATE CHANGE ON AFRICAN CROPLAND[1]

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SUMMARY

This study examines the impact of climate change on cropland in Africa. It is based on an 11-country survey of over 9000 farmers administered as part of a Global Environment Facility (GEF) project. Five of the countries are West African: Burkina Faso, Cameroon, Ghana, Niger and Senegal; three are from Southern Africa: South Africa, Zambia and Zimbabwe; two are East African: Ethiopia and Kenya; and Egypt is the sole representative of North Africa. The study uses a Ricardian cross-sectional approach to measure the relationship between the net revenue from growing crops and climate. Net revenue is regressed on climate, water flow, soils and economic variables. The resulting regression explains the role that each variable plays today. We find that net revenues fall as precipitation falls or as temperatures warm across all the surveyed farms. Specifically, the elasticity of net revenue with respect to temperature is -1.3. This elasticity implies that a 10% increase in temperature would lead to a 13% decline in net revenue. The elasticity of net revenue with respect to precipitation is 0.4.

In addition to examining all farms together, the study examined dryland and irrigated farms separately. Dryland farms are especially climate sensitive. The elasticity of net revenue with respect to temperature is -1.6 for dryland farms but 0.5 for irrigated farms. Irrigated farms have a positive immediate response to warming because they are located in relatively cool parts of Africa. The elasticity of net revenue with respect to precipitation is 0.5 for dryland farms but only 0.1 for irrigated farms. Irrigation allows farms to operate in areas with little precipitation, such as Egypt.

The study also examined some simple climate scenarios to see how Africa would respond to climate change. These ‘uniform’ scenarios assume that only one aspect of climate changes and the change is uniform across all of Africa. For example, the study examined a 2.5°C warming and found that net revenues from farming in all of Africa would fall by $23 billion. It also examined a 5°C warming and found that this would cause net revenues to fall $38 billion. A 7% decrease in precipitation would cause net revenues from crops to fall $4 billion and a 14% decrease in precipitation would cause it to fall $9 billion. Increases in precipitation would have the opposite effect on net revenues.

In addition to the uniform scenarios, the study also examined three climate change scenarios from Atmospheric Oceanic General Circulation Models (AOGCMs). These AOGCM scenarios predicted changes in climate in each country over time. They reveal that African net revenues may rise by up to $97 billion if future warming is mild and wet but would fall by up to $48 billion if future climates are hot and dry. Dryland farms would be affected the most by either beneficial or harmful scenarios. Irrigated farms are relatively resilient to climate change.

Not all countries are equally vulnerable to climate change. First, the climate scenarios predict different temperature and precipitation changes in each country. Second, it is also important whether a country is already hot and dry. Any increase in temperature or reduction in precipitation in these countries leads to large impacts per farm. Third, the extent to which farms are irrigated is also important. Dryland farmers in Africa have little recourse if the climate becomes more hostile.

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1. Introduction

The greatest damages from climate change are predicted to be in the agricultural sector in Sub-Saharan Africa. Agriculture is predicted to be especially vulnerable in this region because it already endures high heat and low precipitation, is a large fraction of the economy, and relies on relatively basic technologies (Pearce et al. 1996; McCarthy et al. 2001). Despite this dire prediction, relatively few economic studies have tried to quantify the damages to African agriculture using African data (Kurukulasuriya & Rosenthal 2003). What little information there is available from agronomic studies (such as Rosenzweig & Parry 1994) suggests that warming would have large effects. Other notable exceptions include some economic analyses of specific crops in regions within selected countries (Molua 2002; Gbetibouo & Hassan 2005; Deressa et al. 2005) and limited agronomic studies (such as Rosenzweig & Parry 1994). These studies suggest that warming would have large effects. But they do not have the scope of this study and cannot completely capture how farmers might respond to warming and thus what the overall economic impacts might be.

This study is based on a cooperative research effort among 11 African countries: Burkina Faso, Cameroon, Egypt, Ethiopia, Ghana, Kenya, Niger, Senegal, South Africa, Zambia, and Zimbabwe. Its purpose is to understand how climate affects current African farmers. Using empirical data about current farmers, the study intends to predict how climate change will be likely to affect future farmers in Africa. The sample of farmers was distributed across many different climate zones so that there would be a great deal of climate variation among the participants. After data cleaning, 9064 surveys of individual farmers were useable (see Table 1).

This study uses the Ricardian method to measure how climate affects net revenues. This method is a cross-sectional technique that measures what determines net revenues to farmers (Mendelsohn et al. 1994; Mendelsohn & Nordhaus 1996; Mendelsohn & Dinar 2003). It has been applied to selected countries in the low latitudes, namely Brazil and India (Sanghi 1998; Mendelsohn et al. 2001), using district level data, and Sri Lanka and Cameroon (Kurukulasuriya & Ajwad 2006; Molua 2002), using household level data, but never across a continent using household level data.

Section 2 briefly reviews the theory behind the Ricardian method and discusses its potential advantages and disadvantages and the empirical specification. Section 3 then discusses the results for Africa and examines regression models for all farms in Africa, dryland farms, and irrigated farms. Section 4 examines the implications of these empirical results given a set of uniform climate change scenarios and future climate scenarios based on climate models (AOGCMs). The paper concludes with a summary and general policy implications.

2. Theory

The Ricardian method is a cross-sectional approach to studying agricultural production. It was named after David Ricardo (1772–1823) because of his original observation that the value of land would reflect its net productivity. Farmland net revenues (V) reflect net productivity. This principle is captured in the following equation:

$$V = \Sigma P_i Q_i (X, F, H, Z, G) - \Sigma P_x X \qquad (1)$$

where P_i is the market price of crop i, Q_i is the output of crop i, X is a vector of purchased inputs (other than land), F is a vector of climate variables, H is water flow, Z is a set of soil variables, G is a set of economic variables such as market access and P_x is a vector of input prices (see Mendelsohn et al. 1994). The farmer is assumed to choose X to maximize net revenues given the characteristics of the farm and market prices. The Ricardian model is a reduced form model that examines how several exogenous variables, F, H, Z and G, affect farm value.

The standard Ricardian model relies on a quadratic formulation of climate:

$$V = B_0 + B_1F + B_2 F^2 +B_3H +B_4 Z + B_5 G + u \qquad (2)$$

where u is an error term. Both a linear and a quadratic term for temperature and precipitation are introduced. The expected marginal impact of a single climate variable on farm net revenue evaluated at the mean is:

$$E[dV/df_i]= b_{1,i} + 2*b_{2,i} *E[f_i] \qquad (3)$$

The quadratic term reflects the nonlinear shape of the net revenue of the climate response function (Equation 2). When the quadratic term is positive, the net revenue function is U-shaped and when the quadratic term is negative, as in Figure 1, the function is hill-shaped. We expect, based on agronomic research and previous cross-sectional analyses, that farm value will have a hill-shaped relationship with temperature. For each crop there is a known temperature at which that crop grows best across the seasons. Crops consistently exhibit a hill-shaped relationship with annual temperature, although the peak of that hill varies with each crop. The relationship of seasonal climate variables, however, is more complex and may include a mixture of positive and negative coefficients across seasons.

The change in welfare, ΔU, resulting from a climate change from C_0 to C_1 can be measured as follows.

$$\Delta U = V(C_1) - V(C_0) \tag{4}$$

If the change increases net income it will be beneficial and if it decreases net income it will be harmful.

Cross-sectional observations across different climates can reveal the climate sensitivity of farms. The advantage of this empirical approach is that the method not only includes the direct effect of climate on productivity but also the adaptation response by farmers to local climate. This farmer behavior is important because it mitigates the problems associated with less than optimal environmental conditions. Analyses that do not include efficient adaptation (such as the early agronomic studies) overestimate the damages associated with any deviation from the optimum. Adaptation thus explains both the more optimistic results found with the Ricardian method and the generally pessimistic results found with purely agronomic studies.

Adaptation is clearly costly. The Ricardian model takes into account the costs of different alternatives. For example, if a farmer decides to introduce a new crop on his land as climate warms, the Ricardian model assumes the farmer will pay the costs normally associated with growing that new crop. That is, the farmer will have to pay for new seeds and new equipment specific to the crop. The Ricardian model does not, however, measure transition costs. For example, if a farmer has crop failures for a year or two as he learns about a new crop, this transition cost is not reflected in the analysis. Similarly, if the farmer makes the decision to move to a new crop suddenly, the model does not capture the cost of decommissioning capital equipment prematurely. Transition costs are clearly very important in sectors where there is extensive capital that cannot easily be changed. For example, studies of timber (Sohngen et al. 2002) show that modeling the transition is absolutely necessary in order to reflect how difficult it is to change the forest stock. Although agriculture adapts quickly to changes in prices, many intertemporal agricultural studies argue that farms will have more difficulty adapting quickly to climate change (Kaiser et al. 1993a,b; Kelly et al. 2005). Given how slowly some innovations in modern agriculture have spread in Africa in particular, transition costs may be very important.

Another drawback of the Ricardian approach is that it cannot measure the effect of variables that do not vary across space. Specifically, this approach cannot detect the effect of different levels of carbon dioxide since carbon dioxide levels are generally the same across the world. Changes in carbon dioxide levels have occurred over recent decades. In principle, one might be able to detect the effect of these increases in CO_2 by looking at productivity over time. However, it is impossible to distinguish the effect of the carbon dioxide changes from the much larger effect of technical changes that have occurred across the same time period (Mendelsohn 2005). The best evidence about the magnitude of the fertilization effects of carbon dioxide comes from controlled experiments. These studies report an almost universal fertilization effect for all crops, although the magnitude of this effect varies from crop to crop (Reilly et al. 1996). Reilly reports an average improvement in productivity of 30% associated with a doubling in CO_2. However, these results must be interpreted cautiously because the conditions in the controlled experiments may not be representative of farms across the world. In most cases, the laboratory experiments have been done in near ideal conditions where other nutrients are freely available. In practice, if nutrients are scarce, the fertilization benefits from increased carbon dioxide levels may be lower. Thus in many developing countries, where fertilizers are not fully applied, the actual carbon fertilization benefits may be less than 30%.

Another potential drawback is that the variation in climate that one could observe across space may not resemble the change in climate that will happen over time. For example, the temperature range across space could be small relative to the change in temperature over the next century. This explains why one may not be able to estimate a Ricardian model in small countries. If the range of climates in a country is small, one cannot detect how climate might affect crops. This specific problem does not apply to this study as there is a wide range of climate variation across the sample. However, it may still be true that climates in the future will not resemble any existing climates. For example, the climate could become erratic, leading to precipitation events that are simply not common today. The analysis cannot measure the impact of such changes.

The Ricardian model also assumes that prices remain constant. As argued by Cline (1996), this introduces a bias in the analysis, overestimating benefits and underestimating damages. The Ricardian approach, by relying on a cross section, cannot adequately control for prices since all farms in the same country effectively face the same prices. However, calculating price changes is not a straightforward task, since prices are a function of the global market. Studies that have claimed to take price changes into account have had to make gross assumptions about how world output would change with climate change. These global assumptions also may introduce bias if they are not correct. Further, even analysts who have assumed large agronomic impacts from global warming predict that greenhouse gases would have only a small net effect on aggregate global food supply (Reilly et al. 1996). If aggregate supplies do not change a great deal, the bias introduced by the Ricardian assumption of constant prices is likely to be small (Mendelsohn & Nordhaus 1996). If the supplies of some commodities increased and others decreased, welfare effects would offset each other. In this case the bias could be large relative to the remaining small net effect. However, even in this case the absolute size of the bias would remain small. In a separate analysis, Kumar and Parikh (2001) include prices in their interannual analysis of Indian agriculture. The inclusion of the price terms appears to have little impact on the climate coefficients.

Another valid criticism that has been leveled against the Ricardian analysis concerns the absence of explicit inclusion of irrigation. Cline (1996) and Darwin (1999) both argued that irrigation should be explicitly included in the analysis. This problem has been addressed in the literature by explicitly modeling irrigation (Mendelsohn & Nordhaus 1999; Mendelsohn & Dinar 2003). This study explicitly includes irrigation and also includes measures of flow and runoff.

A final concern about the Ricardian method is that it reflects current agricultural policies. If countries subsidize specific inputs or regulate crops, these policies will affect farmer choices.

The Ricardian results will consequently have these distortions embedded in the results. For example, if a country mandates that a fraction of cropland be devoted to a certain crop, one may well see more of that crop in that country than elsewhere. We can control for such effects using country dummies. In general, we prefer not to place dummies unless there is evidence of a distortion. Nonetheless, if future decision makers eliminate these subsidies or introduce new ones, the empirical results may no longer hold. Policies that differ across countries could contribute to some of the differences in farm net revenue.

3. Data and empirical analyses

The data for this study were collected by national teams. In each country, districts were chosen to get a wide representation of farms across climate conditions in that country. The districts were not representative of the distribution of farms in each country as there are more farms in more productive locations. In each chosen district, a survey was conducted of randomly selected farms. The sampling was clustered in villages to reduce sampling costs.

A total of 9597 surveys were administered across the 11 countries in the study. The number of surveys varied from country to country. (For more information on the survey method and the data collected see Dinar et al. 2006.) Not all the surveys could be used. Some farms did not grow crops (they only raised livestock). Some surveys contained incorrect information about the size of the farm, cropping area or some of the farm operating costs. Impossible values were treated as missing values. It is not clear what the sources of these errors were but field and measurement errors are most likely. They may reflect a misunderstanding of the units of measurement, they may reflect a language barrier, or they may be intentional incorrect answers. The final number of useable surveys is 9064 and their distribution by country is shown in Table 1.

Data on climate were gathered from two sources. We relied on temperature data from satellites operated by the Department of Defense (Basist et al. 2001). The Defense Department uses a set of polar orbiting satellites that pass above each location on earth between 6am and 6pm every day. These satellites are equipped with sensors that measure surface temperature by detecting microwaves that pass through clouds (Weng & Grody 1998). The precipitation data come from the Africa Rainfall and Temperature Evaluation System (ARTES) (World Bank 2003). This dataset, created by the National Oceanic and Atmospheric Association's Climate Prediction Center, is based on ground station measurements of precipitation. The temperatures for each country in the sample are shown in

Table 2 and the precipitation data in Table 3. Note that there is a wide range of climates across the 11 countries in the sample.

It is not self-evident how to represent monthly temperatures and precipitation data in a Ricardian regression model. The correlation between adjacent months is too high to include every month. We explored several ways of defining three-month average seasons. Comparing the results, we found that defining winter in the northern hemisphere as the average of November, December and January provided the most robust results for Africa. This assumption in turn implies that the next three months would be spring, the three months after that would be summer, and August, September and October would be fall (in the north). These seasonal definitions were chosen because they provided the best fit with the data and reflected the mid-point for key rainy seasons in the sample. We adjusted for the fact that seasons in the southern and northern hemispheres occur at exactly the opposite months of the year. We also explored defining seasons by the coldest month, the month with highest rainfall, and solar position, but found these definitions did a poorer job of explaining current agricultural performance.

Soil data were obtained from FAO (2003). The FAO data provide information about the major and minor soils in each location as well as slope and texture. Data concerning the hydrology were obtained from the University of Colorado (Strzepek & McCluskey 2006). Using a hydrological model for Africa, the hydrology team calculated flow and runoff for each district in the surveyed countries. Figure 1 depicts the distribution of estimated long run flow (in m^3) across the continent. Data on elevation at the centroid of each district were obtained from the United States Geological Survey (USGS 2004). The USGS data are derived from a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately one kilometer).

The literature has made it clear that irrigation and water availability is an important variable in crop production. Irrigated land is generally considered to be of the highest value. However, in Africa most agricultural areas rely on rain (nearly 80%). We explore in this analysis the effect of irrigation on the climate response functions of farmers in different regions of Africa. The irrigation variable is based on plot specific data on water sources. If any primary plot on a farm was using water sources other than rainfall, such as surface water resources, ground water or stored water, in any season of the survey year, the plot was assumed to be irrigated. Table 1 provides a breakdown of where irrigation is employed by country based on the survey data. It is evident that irrigation plays a prominent role in Egypt and South Africa and also in places such as Cameroon, Kenya and Zimbabwe.

Figure 2 depicts the mean net revenue for dryland and irrigated farms in each country in the sample. Net revenue is gross revenue minus the costs of transport, packaging and marketing, storage, post-harvest losses, hired labor (valued at the median market wage rate), light farm tools (such as files, axes, machetes), heavy machinery (tractors, ploughs, threshers and others), fertilizer and pesticide. The median prices per district were used to value both crops and inputs whenever possible. In some circumstances, it was necessary to rely on median provincial or national prices. We excluded household labor in the definition of net revenue because including it led to many households having negative net revenues. This was the case whether we used the payments each household alleged it gave household workers or whether we assigned market wage rates to household labor. The inclusion of household labor in net revenues is problematic, as reported in the agricultural development literature (Bardhan & Udry 1999). We therefore defined net revenues without household labor costs and controlled for the effect of household labor by including adult and child man-days as an independent variable.

Table 4 presents the median net revenue in each country for irrigated and dryland farms. It is evident from Figure 2 and Table 4 that Egypt is a unique case in Africa. Farming in Egypt is predominantly irrigated and technology intensive, leading to significantly higher earnings. A large proportion of Egyptian farmers are also able to cultivate for two seasons, which gives them another advantage over dryland farmers in the rest of our sample.

Following the theoretical model described in Section 2, we estimated multiple regression models of net revenue across three samples (see Table 6). This initial set of regressions does not control for regional differences across Africa. The set examines three models: the entire sample (all farms), just irrigated farms, and just dryland farms. The coefficients for irrigated and dryland farms are not the same, suggesting they have different relationships with the independent variables. While we do not present the results here, a number of farmer specific variables, such as gender, education and whether or not the farmer was a full time farmer or not, were not significant and so were dropped. Overall the three regressions explain 35%, 17% and 29% of the variation in net revenues from farm to farm. The coefficients of the models are significantly different from zero. The variables identify many reasons why farm net revenue varies from place to place. However, a great deal of the variation remains unmeasured. This is especially true of dryland farms that vary from small backyard systems to large commercial operations. There are several sources of possible error, including misreporting of net revenue, omitted variables, local or national restrictions, and random annual phenomena.

Many of the control variables were significant. More water flow increases the value of irrigated farms but not dryland farms. Dryland farms are no better off with water flow because the only water they use comes from on farm precipitation. Farm area reduces the value per hectare of farms at a decreasing rate. That is, small farms are more productive on a per hectare basis. Small farms may appear to be more productive because they are using a fixed resource such as household labor over a much smaller piece of land. This is consistent with the finding that the log of household size is positive in the all Africa and dryland models. Higher elevation reduces the value of dryland farms but increases the value of irrigated farms. In general, high elevation is associated with high diurnal temperature variance, which is often hard on crops. However, high elevation may reduce the cost of irrigation as the slopes can be used to capture and move water at low cost.

Technology variables also matter. Whether or not the farm has access to electricity has a positive effect. This may reflect either higher technology or better access to markets. Whether a farm has irrigation increases farm net revenue substantially. This dummy reflects the cost of irrigation because irrigation costs are not subtracted from net revenue (they were not measured in the survey).

Soils also were quite important in the model. Altogether 12 soil types were identified as significant in the Africa sample. Types such as cambic arenosols (qc), rhodic ferralsols with fine texture in hilly to steep regions (frFHS) and calcic yermosols with coarse to moderate texture and in undulating to hilly regions (ykCMUH) were identified as high productivity soils. By contrast, eutric gleysols with coarse texture in undulating areas (geCU), orthic luvisols in moderate to hilly areas (loMH), chromic vertisols with fine texture in undulating areas (vcFU), and chromic luvisols in moderate to steep areas (lcMS) were all particularly unproductive soils. Some of these soil types were unique to small areas and so could not be included in the dryland and irrigated equations.

The effects of the seasonal climate variables vary across the three models in Table 5. Both linear and squared terms are significant in certain seasons, implying that climate has a nonlinear effect on net revenues. It is not obvious from the coefficients in Table 5 how the quadratic seasonal climate variables affect net revenue, because both linear and squared terms play a role. One can see from the negative/positive sign of the quadratic term that the relationship is hill-shaped/U-shaped. However, depending on what temperature is being examined, the marginal impact of a climate variable could be either positive or negative.

In Table 6 we present an alternative specification of the model. We have added regional variables to capture differences across broad regions and a few more technology variables. The regional dummies suggest that West Africa and North Africa are more productive relative to southern Africa. On the contrary, East Africa is less productive than southern Africa. The results of the technology variables are mixed. The coefficient for whether a farm uses heavy machinery is positive, which most likely reflects modern technology. However, the coefficient for whether a farm depends on animal power is insignificant.

In order to interpret the climate coefficients, we calculated the marginal impacts of a change in each climate variable. The marginal values depend on the regression equation that is being used and the climate that is being evaluated. Table 7 displays the results of using the three regressions from Table 5 and from Table 6. In each case the marginal effect of temperature and precipitation is evaluated at the mean for each sample. For example, the marginal effect of temperature on irrigated land is evaluated at the mean temperature of irrigated land and the marginal impact of precipitation on dryland is evaluated at the mean precipitation for dryland. Irrigated farms are located in cooler (19.7°C) and drier (38.3mm/mo) locations compared to dryland farms (22.2°C and 74.1mm/mo). The marginal temperature results are almost identical with or without regional dummies. However, the marginal precipitation results are higher with the regional dummies. Looking at the total sample results with the regional dummies, evaluated at the African mean climate (22.1°C and 61.5mm/mo), the marginal temperature effect is -28.5°C and the marginal precipitation effect is 3.3mm/mo. The marginal temperature effect for dryland farms is almost the same at -26.7°C. By contrast, the marginal effect of a temperature increase on irrigated farms evaluated at their mean temperature is positive 35.0°C. Warmer temperatures increase the net revenues of irrigated farms because the mean temperature of irrigated farms is relatively cool and because irrigation buffers net revenues from temperature effects. The marginal precipitation effects for dryland and irrigated farms are more similar (3.8/mm/mo for irrigated farms and 2.7/mm/mo for dryland) because irrigated farms are located in such dry locations.

In addition to marginal effects, another important perspective to look at is the climate elasticities (the percentage change in net revenues for a percentage change in climate). Because the mean net revenue of irrigated cropland ($1367/ha) is much higher than the net revenue from dryland cropland ($360/ha), the climate elasticities for irrigated land are smaller. For example, the temperature elasticity for dryland is -1.9 but the elasticity for irrigated land is +0.6. This reflects a dryland farm sensitivity to climate that is nearly three times that of irrigated farms and in the opposite direction. The precipitation elasticity for dryland is +0.6 but the elasticity for irrigated land is +0.1. The net revenues from irrigated land are relatively less climate sensitive than those of dryland.

In order to provide a more complete sense of the climate response functions implied in Table 5, we plotted the net revenues of an average farm at different temperatures and rainfall levels. Figures 3a and 3b illustrate the average results for the entire sample of farms (mixing irrigated and dryland farms together). Figures 3a and 3b clearly show that net revenues decline with temperature and rise with precipitation in Africa. The shape of the temperature function, however, is worth noting. Results from Ricardian regressions estimated in the United States (a temperate country) implied a hill-shaped function. Because of its hot initial temperature, Africa lies on the right hand side of this hill, implying warming would have large negative impacts (Mendelsohn et al. 1994; 1999; 2001). Although the results in Africa are consistent with a hill-shaped model, they imply that the net revenues decline gently rather than precipitously. Estimating the Ricardian model with African data reveals that there are additional crops and methods suited to these higher temperatures which may not have been used in a region with a temperate climate such as the US. It is also worth noting with regard to Figure 3b that precipitation increases are generally beneficial to crops in Africa because it is so dry to start with.

Figures 4a and 4b examine the response function of dryland alone. Most African farms use dryland methods so the response function for dryland looks quite similar to the response function for all of Africa. The temperature and precipitation functions are slightly steeper for dryland than for all farms but the difference is not significant.

Figures 5a and 5b illustrate the temperature and precipitation response functions for irrigated cropland. These response functions reveal that higher temperatures reduce net revenues per hectare but at a rate of reduction that is lower than for dryland farms. Irrigated farms appear to be more resilient to higher temperatures. The precipitation response function for these farm types suggests (as expected) higher revenue per hectare with additional precipitation.

4. Forecasts of climate impacts

We used the estimated response functions to explore how climate change scenarios might affect cropland in all of Africa. The Ricardian model estimates how climate affects net revenue per hectare. In order to extrapolate from the sample to the entire continent, however, it is necessary to know how many hectares of cropland there are in each district. In this paper, we rely on estimates by the IFPRI (International Food Policy Research Institute) and FAO of the amount of cropland in each district (Lotsch 2006, FAOStat 2005). The map of cropland is shown in Figure 6. The primary arable land areas are in the temperate regions of North Africa, the coastal belt in West Africa (south of the Sahel) and along the Rift Valley in Eastern and Southern Africa.

Because we intended to explore the effects of climate on dryland and irrigated land, we needed to determine which land across Africa is irrigated. We relied on FAO estimates of the total hectares of irrigated cropland in each country (FAOStat 2005, Siebert et al. 2005). We allocated these hectares across districts within each country on the basis of the districts' respective climates. The probability of irrigation in each district was interpolated using a probit model that regressed irrigation on a set of independent climate variables including climate, soils and flow (the regression results can be requested from the authors). Figure 7 shows the irrigation results, which suggest that coastal regions in North Africa and southern Africa have a higher likelihood of irrigation. Other regions of Africa, particularly central Africa and regions along the Rift Valley, either have sufficient rainfall and/or lack the investment necessary to undertake irrigation. Note that the estimate of the amount of cropland and the percent of irrigation is based solely on current climate and is assumed not to change. The question of whether cropland and irrigation are sensitive to climate is taken up in other papers as part of this project.

Uniform scenarios

We began the analysis of the effect that climate change is likely to have on African farms, ceteris paribus, by examining some uniform climate change scenarios. The uniform climate scenarios provided a simple set of climate changes that allow one to see how the model behaves and which components of climate are important.

Using the estimated regression coefficients in Table 5, we examined how changes in climate change net revenue per hectare in each district throughout Africa (Equation 4). We then multiplied the change in net revenue per hectare by the number of hectares of cropland in each district to get an aggregate impact in each district. This value was then summed across all the districts of Africa to get a total impact for a country or for the continent:

$$\text{Aggregate climate impact}_d = \text{Sum}(\Delta Y_i * W_j) \tag{5}$$

where ΔY_i = change in net revenue per hectare from a climate change

W_j =hectares of cropland, irrigated cropland or dryland cropland

d= district d

The results of the uniform climate scenarios are presented in Table 8. Four uniform climate scenarios were tested: changes of +2.5°C, +5°C, -7% precipitation, and -14% precipitation. The 2.5°C warming results in predicted losses of $23 billion for dryland, a gain of $1 billion for irrigated cropland, and a loss of $16.4 billion for all African cropland. The separate temperature impacts for dryland and irrigated cropland are greater than the impacts for the total sample. The analysis of the total sample allows land to change between dryland and irrigation as temperature rises, reducing the extent of the damage. Doubling warming to 5°C increases the benefits to irrigation to $3.4 billion but the losses to dryland increase to $38 billion and all African cropland to $31 billion. Reducing precipitation reduces both dryland and irrigated land net revenue about the same amount on a per hectare basis. Curiously, reductions in precipitation are predicted to cause much larger losses in the total sample than in the component parts.

Figure 8a depicts the geographic distribution of impacts from a uniform warming of 2.5°C. Although the warming is assumed to be the same in every district, the impact depends on the initial temperature of the district. Figure 8a shows that net revenues in districts in and near the Sahara desert and in southern Africa fall the most with uniform warming. Districts across the equator are much less affected (±$25/ha) relative to per hectare impacts in other regions. Doubling warming to 5°C (Figure 8b) does not change the distribution of impacts across

Africa a great deal but it does increase the magnitude of the losses in districts that are damaged. Reducing precipitation (Figure 8c) has a much larger harmful effect on the wetter parts of Africa. The central humid band of the continent bears the brunt of the damage in this scenario. Doubling the precipitation loss to 14% (Figure 8d) increases the magnitude of the losses and their extent near the humid zone and equatorial Africa.

AOGCM scenarios

We also examined a set of climate change scenarios predicted by Atmospheric-Oceanic Global Circulation Models (AOGCMs). We relied on three scenarios consistent with the range of outcomes in the most recent IPCC (Intergovernmental Panel on Climate Change) report (Houghton et al. 2001). Specifically, we used the A1 scenarios from the following models: CCC (Canadian Climate Centre) (Boer et al. 2000), CCSR (Centre for Climate System Research) (Emori et al. 1999), and PCM (Parallel Climate Model) (Washington et al. 2000). In each of these scenarios, climate changes at the grid cell level were summed to predict climate changes by country. We then examined the consequences of these country level climate change scenarios for 2020, 2060, and 2100.

For each climate scenario, we added the predicted change in temperature from the climate model to the baseline temperature in each district. We also multiplied the predicted percentage change in precipitation from the climate models by the baseline precipitation in each district or province. This gave us a new climate for every district in Africa. Table 9 presents the mean temperature and rainfall predicted by the three models for the years 2020, 2060 and 2100. In Africa in 2100, PCM predicts a 2°C increase, CCSR a 4°C increase and CCC a 6°C increase in temperature. Rainfall predictions are noisier: PCM predicts a 10% increase in rainfall in Africa, CCC a 10% decrease, and CCSR a 30% decrease. Even though the mean rainfall in Africa is predicted to increase/decrease depending on the scenario, there is substantial variation in rainfall across countries.

Examining the path of climate change over time reveals that temperatures are predicted to increase steadily until 2100 for all three models. Precipitation predictions, however, vary across time for Africa: CCC predicts a declining trend; CCSR predicts an initial decrease, and then increase, and decrease again; PCM predicts an initial increase, and then decrease, and increase again. However, it should be noted that because the AOGCMs make geographically detailed predictions the predicted changes for individual countries vary.

We applied the same methodology as outlined above for the uniform climate scenarios. We first calculated the level of farm net revenue under current conditions and then the level of net revenue under each climate scenario. The net revenues were predicted using the estimated regression coefficients from Table 6. The change in net revenue was then multiplied by the hectares of cropland in that district. These impacts were then summed across all districts in Africa. We relied on the same underlying predictions of the quantity of cropland and irrigation as with the uniform scenarios. Of course, with the AOGCM scenarios the predicted change in net revenues will be different depending on the climate scenario.

In Table 10 we present the results of the nine scenarios: for the three models in three time periods. The PCM results suggest that with ample rainfall and only a small increase in temperature the net effect on all African farms would be a gain of from $87 to $97 billion per year. The CCSR results suggest that substantial drying and warming together would generate losses of from $19 to $27 billion beyond 2060 across Africa. The CCC results suggest that a large warming of 6C would lead to substantial losses across African farms equal to $48 billion by 2100. Irrigated farms are predicted to benefit across all but one of these scenarios, partly because they are climate insensitive and partly because they are located in relatively cool areas. Dryland farms are likely to be affected the most, whether it is a benefit of $72 billion or a loss of $44 billion.

Figures 9 to 11 illustrate the distribution of impacts given that each country will face its own climate scenario. Figures 9a, 9b, and 9c illustrate the impacts per hectare from the PCM climate regimes for 2020, 2060, and 2100. According to the PCM model, climate changes cause African net revenues to rise in all three time periods over the next century. Moderate temperature changes and favorable precipitation generally increase African productivity (although not necessarily as much as in other regions of the world). However, there are three bands of land stretching from east to west across Africa where net revenues fall: along the Mediterranean coast, from Kenya through West Africa, and across the southern tip of Africa. These three bands of land experience moderate to high losses in all three time periods.

Figures 10a, 10b, and 10c illustrate the impacts according to the CCSR climate scenarios. The 2020 CCSR scenarios are predicted to lead to significant losses per hectare in all of northern, western and southwestern Africa. By contrast, farms in the central humid region experience large benefits and farms in much of eastern and southeastern Africa experience moderate benefits. In 2060, the CCSR scenario limits benefits strictly to the humid region of

Africa while the rest of Africa experiences drought conditions. In 2100, farms in many parts of the continent continue to suffer from reduced rainfall except for the humid central region and parts of eastern Africa. Niger, Mali, Somalia and other traditionally dry regions benefit from this scenario, because CCSR predicts large increases in rainfall in these regions. The beneficial impacts of the added rain in traditionally dry regions can outweigh the harmful effects of higher temperatures. In the CCC scenarios (Figures 11a–c) much of Africa is vulnerable to adverse impacts except for the West African coast, the humid center, and the northeast. The damages in regions that are harmed get more severe over time with the CCC scenario as temperatures are predicted to rise rapidly.

It is also helpful to remember where the people are living in order to judge which impacts will be the most severe in human terms. Figure 12 provides a population density map of Africa (CIESIN 2004). In conjunction with Figures 9, 10, and 11, one can see where climate change may affect the most people. The population map indicates that West Africa (south of the Sahel), the Mediterranean coastline, and a band across central Africa and a north to south band in Eastern Africa are among the most densely populated. These areas coincide with regions that the CCC and CCSR climate predictions suggest will be harmed. Even the impacts from the relatively more favorable climate scenario based on the PCM models suggest that populated regions such as the Mediterranean coastline, southern Africa and central Africa will be severely affected. The results suggest that the impacts on rural populations in Africa from climate change are likely to be significant.

5. Conclusions and implications for policy

This study is a cross-sectional analysis of the net revenues of African farms, relying on the Ricardian method to investigate the impact of climate on net revenues, and building on a massive data effort to collect information about farmers in 11 African countries. Surveys of over 9000 African farms were combined with detailed measurements of soils, climate, hydrology and elevation from a number of sources.

The study found that African farms are indeed sensitive to climate and especially temperature. It predicts that farm values will decline if temperatures rise. Specifically, the temperature elasticity with respect to net revenue of African farms is estimated to be -1.3. The precipitation elasticity is estimated to be 0.4. The sensitivity is the greatest for dryland farms with a temperature elasticity of -1.6 and a precipitation elasticity of 0.5. Irrigated farms, by contrast, are resilient to temperature changes and may actually increase in value (partly because of their location in temperate regions of Africa).

The study examined the impacts of future scenarios from climate models. Mild climate scenarios predict future benefits across African cropland for irrigated and especially dryland farms. Yet even in these favorable scenarios regions in the Mediterranean, central, western and southern Africa that are currently productive stand to be adversely affected. More dramatic warming scenarios predict small damages by 2020 that increase steadily over time. These damages are exacerbated by drying. For example, the CCSR scenario predicts extreme drying that leads to damages of $26 billion for dryland by 2060. For Africa as a whole, the harmful scenarios predict losses from $27 to $48 billion by the end of the century, whereas the beneficial scenario predicts gains of $97 billion. There is a wide range of possible outcomes across these plausible climate scenarios.

The study found that impacts are not likely to be uniform across Africa. The hotter and drier regions of Africa are likely to be hurt the most. The distribution of impacts across Africa also depends on the climate scenario. Finally, how many people are affected depends on where they are located. Putting all these factors together, it is hard to predict what actually will happen in Africa. There remains a wide range of plausible outcomes. It is even more difficult to predict what will happen in specific places. However, it is evident from this study that Africa will be affected by climate change.

The study suggests that African countries should begin to plan for climate contingencies. Governments should begin to develop contingency plans if certain climate outcomes come to pass. They should anticipate what farmers will do, how markets will react, and what role governments need to play. Governments should be prepared to help people adapt to these new circumstances.

Some actions can also be taken before climate changes. Actions that make agriculture sectors more immune to climate can be taken in advance. Developing new crops and livestock that are more suited to hot and dry conditions will help countries adapt to many current climate zones as well as future ones. Developing profitable irrigated agriculture systems will reduce the climate vulnerability of the agriculture sector. Developing the economy away from agriculture will reduce the climate sensitivity of the entire economy. Increasing wealth so that firms and households can explore more alternatives will make adaptation easier.

The impacts of warming on African agriculture are significant. This study confirms what scientists have long suspected. Dryland farmers in Africa will be vulnerable to increases in temperature. Although farmers have some adaptations available to them, such as switching to more heat tolerant crops, if they continue with their current technology warming will have a devastating effect on dryland farmers. African agriculture appears to be extremely vulnerable to climate change. However, not all of Africa is likely to experience the same effects from it. The humid regions of Africa are likely to be less vulnerable to warming than the drier northern and southern regions. Exactly how climate change will affect individual countries varies a great deal across climate models.

There are two important factors that must be considered that were not included in this analysis. First, this study takes the technology of each farmer as given. There is no doubt about the importance of technology. The average dryland farmer earns \$319/ha whereas the average irrigated farmer earns \$1261/ha. The more advanced irrigated farms earn even more. What will happen to technology in Africa's future is very important. The second important factor left out of this analysis is carbon fertilization. Experimental results suggest that yields could increase on average by 30% if CO_2 doubles (Reilly et al. 1996). If these gains are realized in the field, they will help to offset a great deal of the otherwise inevitable harmful effects of warming.

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Table 1: Useable surveys by country

Country	Dryland	Irrigated	Total
Burkina Faso	990	41	1031
Cameroon	646	105	751
Egypt	0	802	802
Ethiopia	874	66	940
Ghana	849	29	878
Kenya	675	79	754
Niger	849	48	897
Senegal	1037	31	1068
South Africa	199	87	286
Zambia	956	14	970
Zimbabwe	597	90	687
Total	**7672**	**1392**	**9064**

Table 2: Temperature (°C) normals (Sample means)

Country	Winter	Spring	Summer	Fall
Burkina Faso	23.6	28.3	28.9	24.5
Cameroon	19.4	21.4	20.0	18.9
Egypt	11.7	13.2	24.1	23.4
Ethiopia	18.6	21.5	19.7	18.1
Ghana	21.8	24.8	22.6	21.2
Kenya	18.8	19.7	18.4	19.1
Niger	26.3	30.8	33.9	29.2
Senegal	24.5	29.1	31.5	26.7
South Africa	11.5	15.5	20.7	19.4
Zambia	16.7	21.7	21.1	19.6
Zimbabwe	16.6	21.3	22.5	20.6
Africa-wide	**19.8**	**23.4**	**24.5**	**22.2**

Note: Seasonal climates have been adjusted so that they are consistent regardless of hemisphere.

Table 3: Precipitation (mm/mo) normals (Sample means)

Country	Winter	Spring	Summer	Fall
Burkina Faso	2.6	15.8	113.8	133.1
Cameroon	60.3	101.9	185.1	228.6
Egypt	12.8	7.0	2.3	3.5
Ethiopia	19.4	49.2	123.7	117.5
Ghana	30.9	59.7	112.4	111.7
Kenya	88.4	103.0	84.3	60.0
Niger	0.8	3.2	64.1	70.6
Senegal	2.2	1.1	47.9	112.7
South Africa	1.8	55.0	86.4	68.8
Zambia	48.3	57.7	108.6	100.7
Zimbabwe	7.5	15.4	138.8	90.0
Africa-wide	**25.9**	**39.8**	**96.1**	**102.4**

Note: Seasonal climates have been adjusted so that they are consistent regardless of hemisphere.

Table 4: Net revenues per ha (in US$)

Country	Total	Dryland	Irrigated
Burkina Faso	328	318	538
Cameroon	987	952	1217
Egypt	1660		1660
Ethiopia	199	188	345
Ghana	422	419	496
Kenya	267	255	365
Niger	125	119	227
Senegal	239	237	282
South Africa	811	538	1445
Zambia	134	133	145
Zimbabwe	432	403	643
Average per ha	**462**	**319**	**1261**

Table 5: Regression coefficients of all farms, dryland farms and irrigated farms without regional dummies

Variable	All farms	Dryland	Irrigated
Winter temperature	-83.9	-117.1*	91.0
Winter temp squared	2.98*	3.62*	-2.16
Spring temp	-18.4	-20.9	-186.3
Spring temp sq	-1.61	-1.10	2.21
Summer temp	212.4**	118.9	1093.0**
Summer temp sq	-2.74**	-1.36	-19.01**
Fall temp	-116.6*	-22.8	-1067.4**
Fall temp sq	1.68	-0.23	22.28**
Winter precipitation	-3.32**	-4.79**	7.86
Winter prec sq	0.018**	0.025**	-0.043
Spring prec	3.42*	5.38**	-11.99
Spring prec sq	-0.002	-0.017**	0.099*
Summer prec	3.90**	3.43**	23.84**
Summer prec sq	-0.016**	-0.015**	-0.093**
Fall prec	-1.63*	-1.76**	-19.82**
Fall prec sq	0.012**	0.013**	0.074**
Mean flow	12.20**	-8.48*	10.54**
Farm area	-0.074**	-0.320**	-0.042*
Farm area sq	0.000**	0.000**	0.000*
Elevation	-0.077**	-0.115**	0.234*
Log (household size)	27.3*	20.93	64.5
Irrigate (1/0)	251.3**		

Table 5 (continued):

Variable	All farms	Dryland	Irrigated
Household access to electricity (1/0)	117.4**	95.47**	297.8**
Soil (geCU)	-692.4**	-393.3**	-1265.7**
Soil (ilqHS)	-454.4**	-228.1**	-1038.0**
Soil (loMH)	-2322.0**	-1999.8**	
Soil (vcFU)	-1065.1**	-894.3**	-1585.5**
Soil (lcMFU)	-261.2**	-250.2**	
Soil (qc)	1642.8**	1709.0**	
Soil (ql)	-539.9**	-269.6**	
Soil (lcMS)	-2267.6		-5812.3**
Soil (nd)	370.7		7343.7**
Soil (lg)	-179.0**	-125.2**	
Soil (frFHS)	992.4*		3540.0
Soil (ykCMUH)	1279.6**	-636.3**	
Constant	141.8	702.4	-243.3
N	8459	7238	1221
R2	0.351	0.171	0.29
F	68.59	33.81	52.45

Notes: * significant at 5% level ** significant at 1% level

Soil definitions: Rhodic ferralsols with fine texture in hilly to steep areas (frFHS), eutric gleysols with coarse texture in undulating areas (geCU), lithosols hilly to steep slope (ilqHS), chromic luvisols with medium to fine texture in undulating areas (lcMFU), chromic luvisols in moderate to steep areas (lcMS), gleyic luvisols (lg), orthic luvisols in moderate to hilly areas (loMH), dystric nitrosols (nd), cambic arenosols (qc), luvic arenosols (ql), chromic vertisols with fine texture in undulating areas (vcFU), calcic yermosols with coarse to moderate texture and in undulating to hilly areas (ykCMUH), lithosols in hilly and steep areas (ilqHS), luvic arenosols (ql), dystric nitosols (nd), gleyic luvisols (lg).

Table 6: Regression coefficients of all farms, dryland farms and irrigated farms with regional dummies

Variable	All farms	Dryland	Irrigated
Winter temperature	-173.6**	-106.7	-93.5
Winter temp squared	6.1**	3.9*	4.9
Spring temp	115.1	-82.8	58.7
Spring temp sq	-5.0**	-0.3	-4.1
Summer temp	173.9**	198.6**	827.5**
Summer temp sq	-1.9	-3.2*	-13.1*
Fall temp	-98.1	-92.4	-824.2*
Fall temp sq	1.1	1.5	15.3*
Winter precipitation	-2.9*	-1.9	5.8
Winter prec sq	0.0**	0.00	0.00
Spring prec	3.5*	3.6**	-10.6
Spring prec sq	-0.001	-0.011*	0.091*
Summer prec	3.4**	1.9*	21.4**
Summer prec sq	-0.012**	-0.005	-0.086**
Fall prec	-0.5	-0.6	-14.7**
Fall prec sq	0.0055*	0.0053*	0.0586***
Mean flow	9.4**	-5.4	8.8**
Farm area	-0.1**	-0.3**	-0.0**
Farm area sq	0.0*	0.0**	0.0*
Elevation	0.035	-0.0009	0.229
Log (household size)	22.9	10.1	62.4
Irrigate (1/0)	237.5**		
Household access to electricity (1/0)	66.6**	47.7**	233.2*

Table 6 (continued):

Variable	All farms	Dryland	Irrigated
Soil (geCU)	-631**	-287**	-540
Soil (ilqHS)	-387**	-156**	-1147**
Soil (loMH)	-2181**	-1959**	
Soil (vcFU)	-1180**	-1006**	-1719**
Soil (lcMFU)	-295**	-241**	
Soil (qc)	1633**	1726**	
Soil (ql)	-482**	-188**	
Soil (lcMS)	-2153		-6157**
Soil (nd)	214		7051**
Soil (lg)	-199**	-154**	
Soil (frFHS)	1428**		3212
Soil (ykCMUH)	1071**	148	
West Africa dummy	136**	208**	-285
North Africa dummy	457**		675*
East Africa dummy	-186**	-154**	-361
Heavy machinery dummy	51.8**	55.5**	-60.8
Animal power dummy	10.4	49.3**	-185.5**
Constant	-388	1081	-549
N	8459	7238	1221
R2	0.4	0.2	0.3
F	63.6	32.4	46.3

Notes: * significant at 5% level ** significant at 1% level

Soil definitions: Rhodic ferralsols with fine texture in hilly to steep areas (frFHS), eutric gleysols with coarse texture in undulating areas (geCU), lithosols hilly to steep slope (ilqHS), chromic luvisols with medium to fine texture in undulating areas (lcMFU), chromic luvisols in moderate to steep areas (lcMS), gleyic luvisols (lg), orthic luvisols in moderate to hilly areas (loMH), dystric nitrosols (nd), cambic arenosols (qc), luvic arenosols (ql), chromic vertisols with fine texture in undulating areas (vcFU), calcic yermosols with coarse to moderate texture and in undulating to hilly areas (ykCMUH), lithosols in hilly and steep areas (ilqHS), luvic arenosols (ql), dystric nitosols (nd), gleyic luvisols (lg).

Table 7: Marginal impacts of climate on net revenue (US$/ha)

(Evaluated at the mean of the Africa, irrigated and dryland sample)

Without regional dummies (From coefficients in Table 5)

Sample	**Africa regression**	**Irrigated regression**	**Dryland regression**
Temperature	-28.3**	33.6	-23.0**
	(-1.3)	(0.5)	(-1.6)
Precipitation	2.65**	2.08	2.02**
	(0.36)	(0.06)	(0.47)

With regional dummies (From coefficients in Table 6)

Annual	**Africa regression**	**Irrigated regression**	**Dryland regression**
Temperature	-28.5**	35.04	-26.7**
	(-1.4)	(0.6)	(-1.9)
Precipitation	3.28**	3.82	2.7**
	(0.44)	(0.13)	(0.63)

** significant at 1% level

Table 8: Africa-wide impacts from uniform climate scenarios

Impacts	2.5°C warming	5°C warming	7% decreased precipitation	14% decreased precipitation
Dryland				
ΔNet revenue	-72.2	-120.4	-14.1	-28.3
($ per ha)	*(-16%)*	*(-30%)*	*(-6%)*	*(-11%)*
ΔTotal net revenue (billions $)	-22.6	-37.7	-4.4	-8.9
Irrigated				
ΔNet revenue	110.3	258.8	-15.9	-31.5
($ per ha)	*(9%)*	*(23%)*	*(-1.4%)*	*(-2.7%)*
ΔTotal net revenue (billions $)	1.4	3.4	-.21	-0.41
Total (Africa)				
ΔNet revenue	-49.2	-95.7	-18.3	-37.2
($ per ha)	*(-11.3%)*	*(-21.9%)*	*(-4.2%)*	*(-8,5%)*
ΔTotal net revenue (billions $)	-16.0	-31.2	-5.96	-12.1

Note: Using coefficients in Table 6 and changes to climate that are uniform across Africa. The numbers in brackets represent the percentage change in net revenue per hectare relative to the mean of the sample.

Table 9: Climate predictions of AOGCM models for 2020, 2060 and 2100

Model		Current	2020	2060	2100
CCC		23.29	24.94	26.85	29.96
CCSR	Temperature	23.29	25.27	26.17	27.39
PCM		23.29	23.95	24.94	25.79
CCC		79.75	76.84	71.86	65.08
CCSR	Precipitation	79.75	73.99	76.67	62.44
PCM		79.75	89.58	80.72	83.18

Table 10: Africa-wide impacts from AOGCM climate scenarios

Impacts	PCM 2020	PCM 2060	PCM 2100	CCSR 2020	CCSR 2060	CCSR 2100	CCC 2020	CCC 2060	CCC 2100
Dryland									
ΔNet Revenue	231.6	196.2	199.7	-12.8	-82.8	-128.9	-72.1	-92.1	-139.0
($ per ha)	*(73.3%)*	*(62.1%)*	*(63.2%)*	*(-4%)*	*(-26%)*	*(-40%)*	*(-22%)*	*(-29.2)*	*(-44%)*
ΔTotal Net Revenue (billions $)	72.4	61.4	62.5	-4.0	-25.9	-40.3	-22.5	-28.8	-43.5
Irrigated									
ΔNet Revenue	468.9	506.5	586.8	76.6	142.3	-420.9	49.1	137.6	297.1
($ per ha)	*(40%)*	*(44%)*	*(51%)*	*(6.7%)*	*(12%)*	*(-36%)*	*(4.3%)*	*(12%)*	*(26%)*
ΔTotal Net Revenue (billions $)	6.1	6.6	7.6	.99	1.8	-5.5	0.6	1.78	3.9
Total (Africa)									
ΔNet Revenue	277.8	268.2	296.8	38.7	-58.7	-82.7	-71.1	-72.6	-148.7
($ per ha)	*(63%)*	*(61.5%*	*(68%)*	*(9%)*	*(-13%)*	*(-19%)*	*(-16%)*	*(-17%)*	*(-34%)*
ΔTotal Net Revenue (billions $)	90.5	87.4	96.7	12.6	-19.1	-26.9	-23.2	-23.6	-48.4

Note: Using coefficients in Table 6 and AOGCM country specific climate scenarios. The numbers in brackets represent the percentage change in net revenue per hectare relative to the mean of the sample.

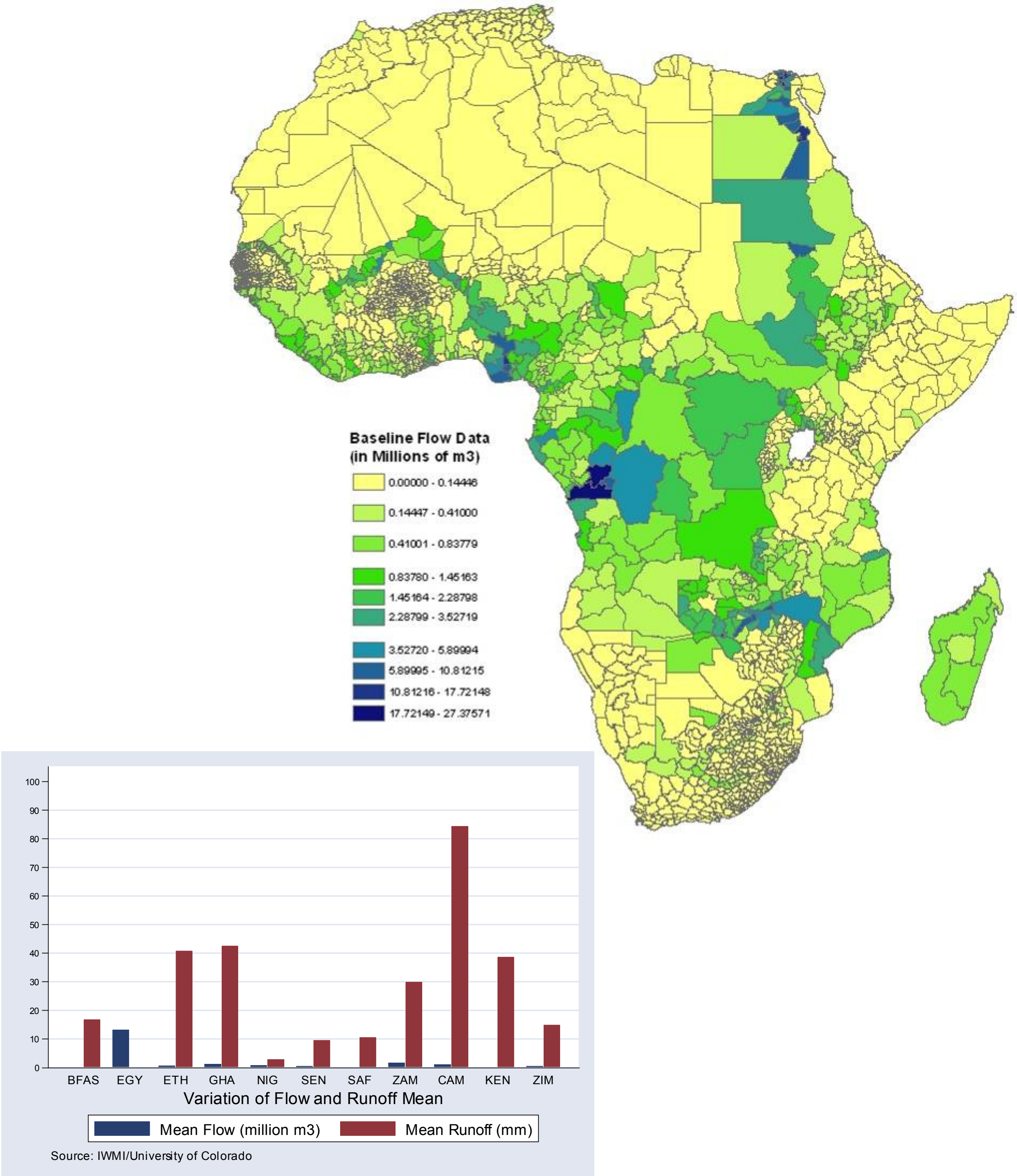


Figure 1: Mean flow (m^3) and runoff (mm)

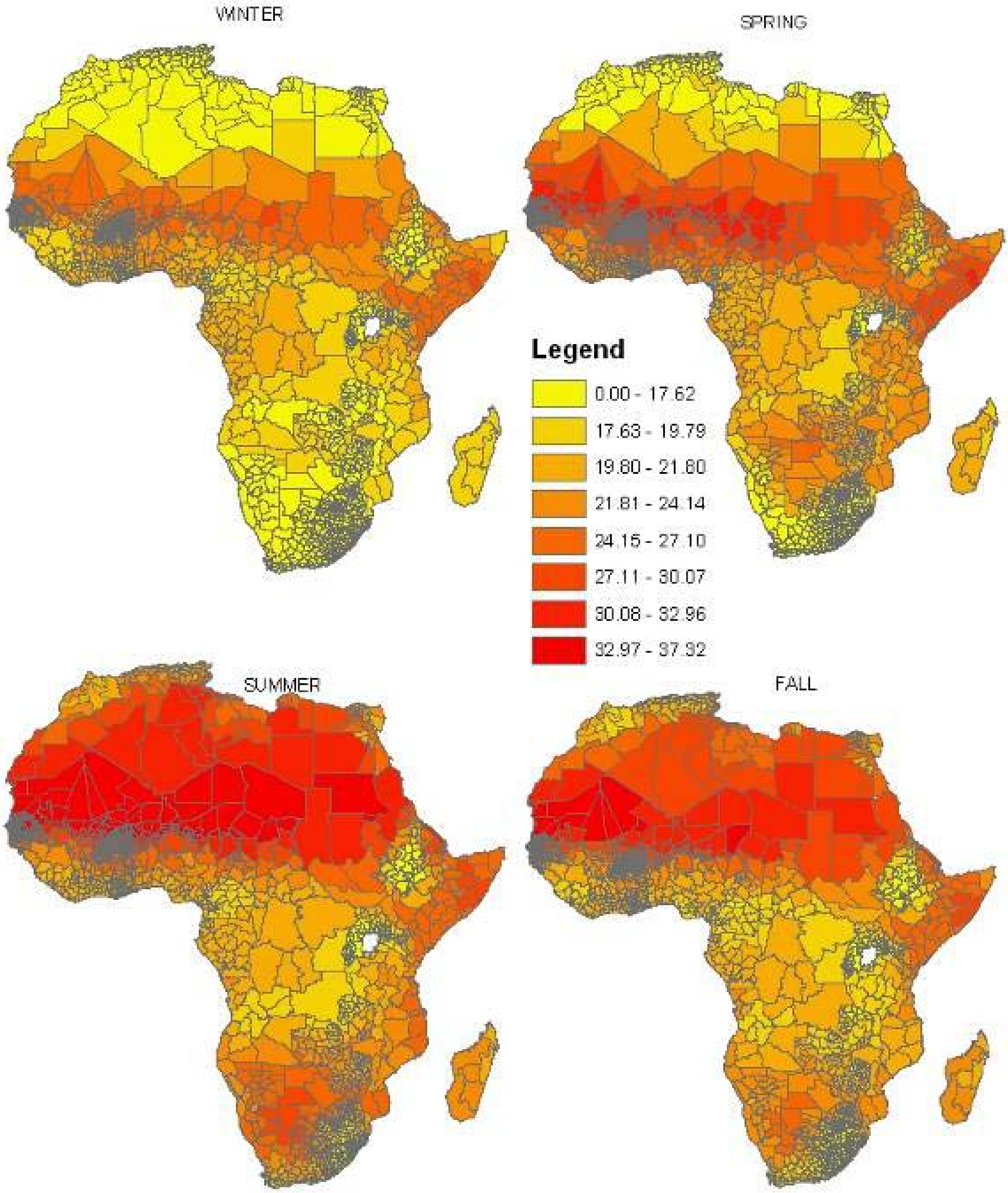


Figure 1b: Long run seasonal mean temperature (°C)

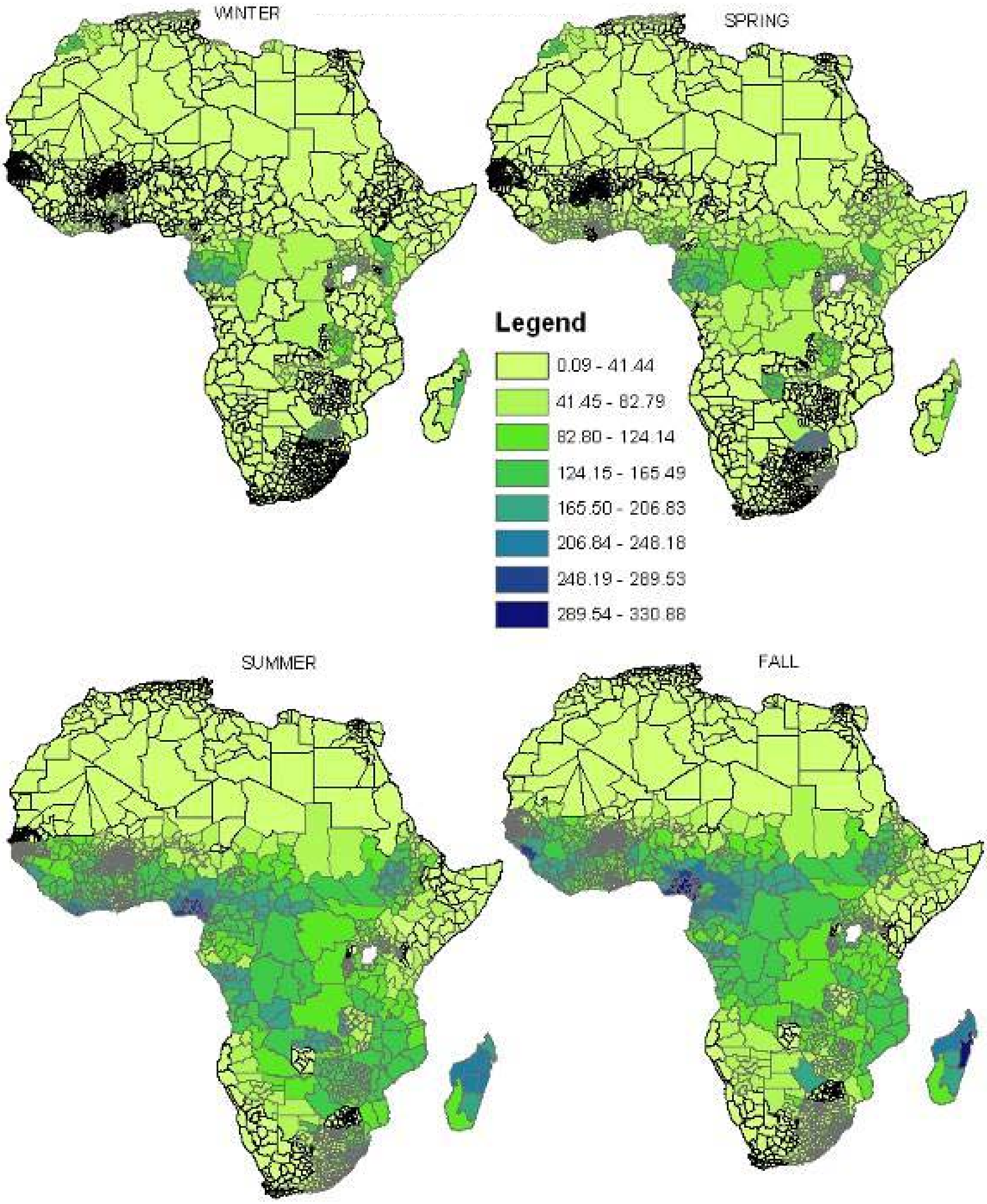


Figure 1c: Long run seasonal mean precipitation (mm/mo)

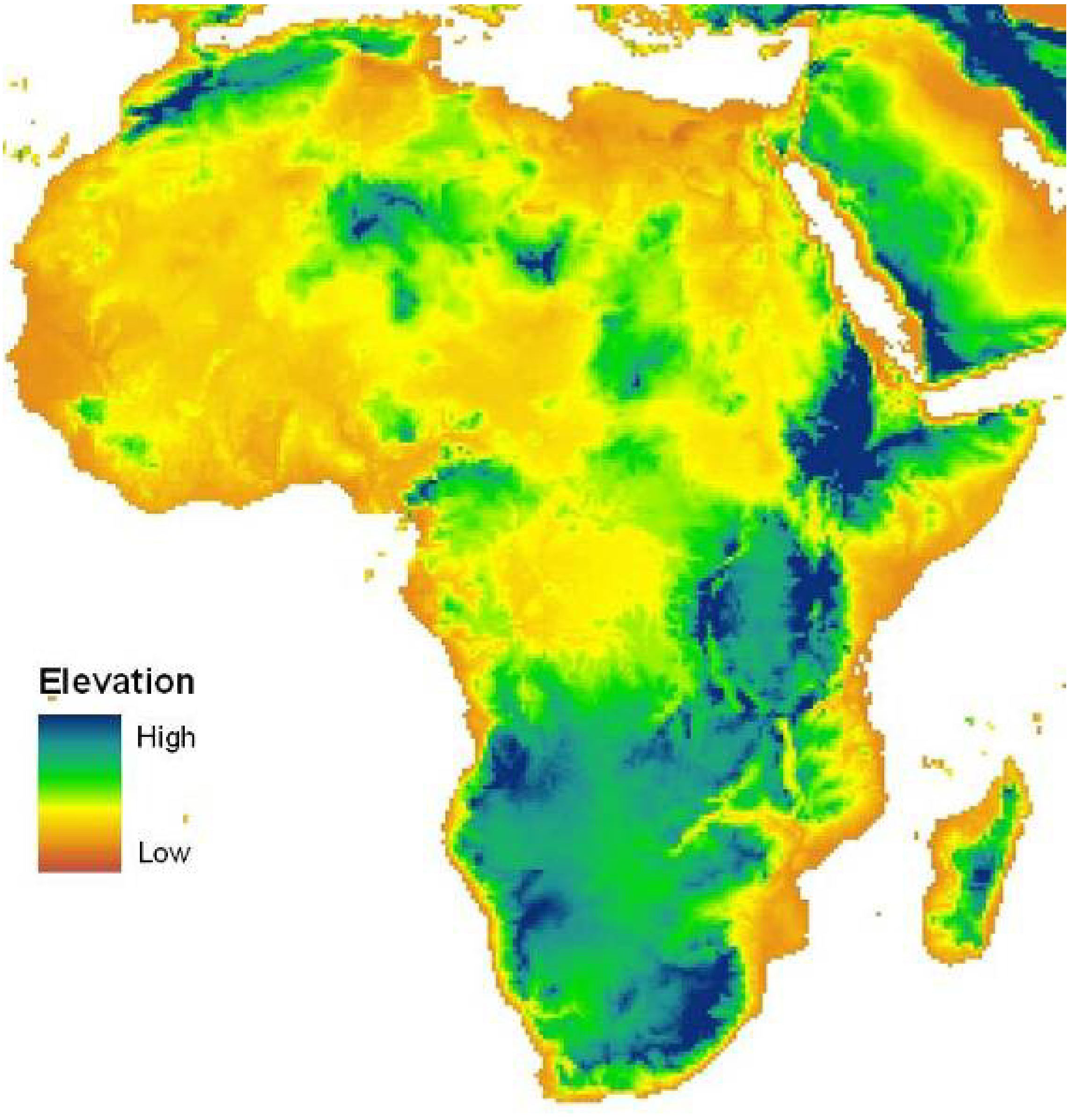
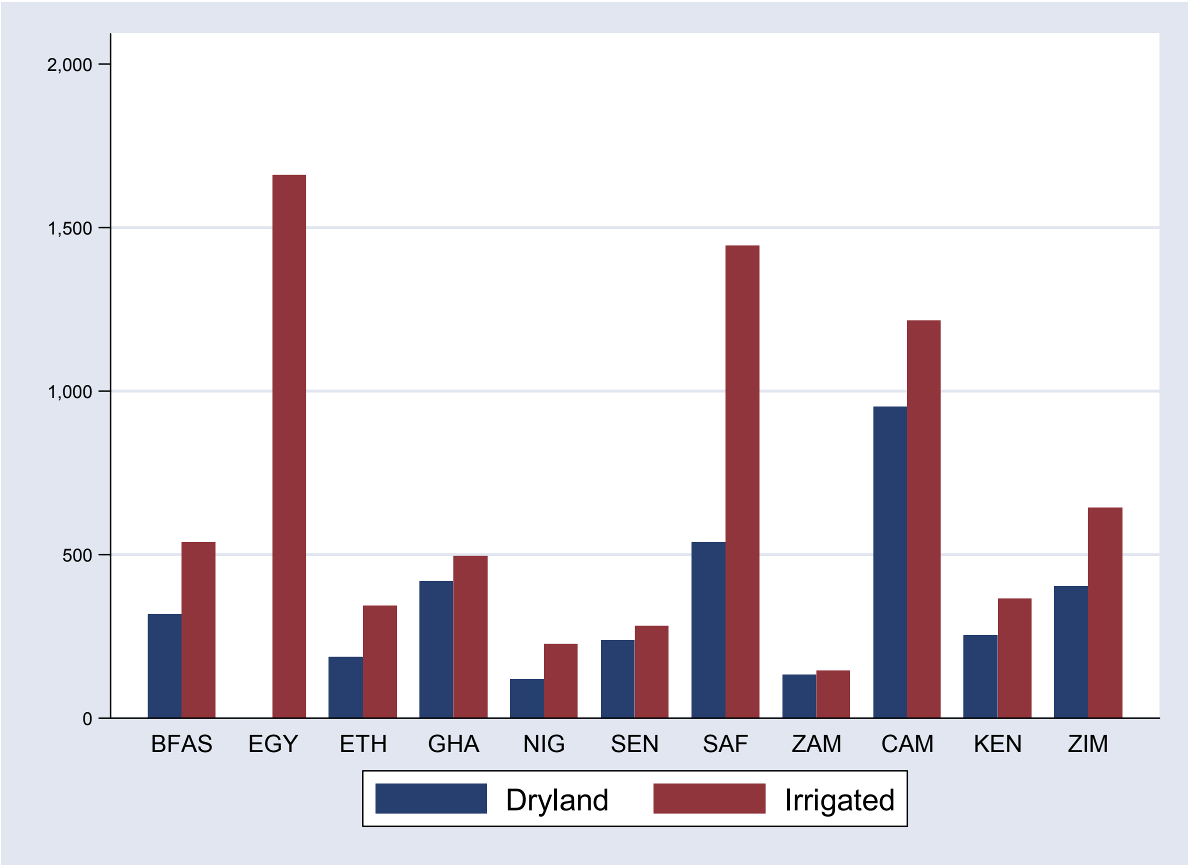


Figure 1d: Elevation (m)



Note: Net revenue = Gross revenue – less total cost of hired labor, small tools and heavy machinery, fertilizer and pesticide

Figure 2: Net revenue per hectare of dryland and irrigated cropland by country ($/ha)

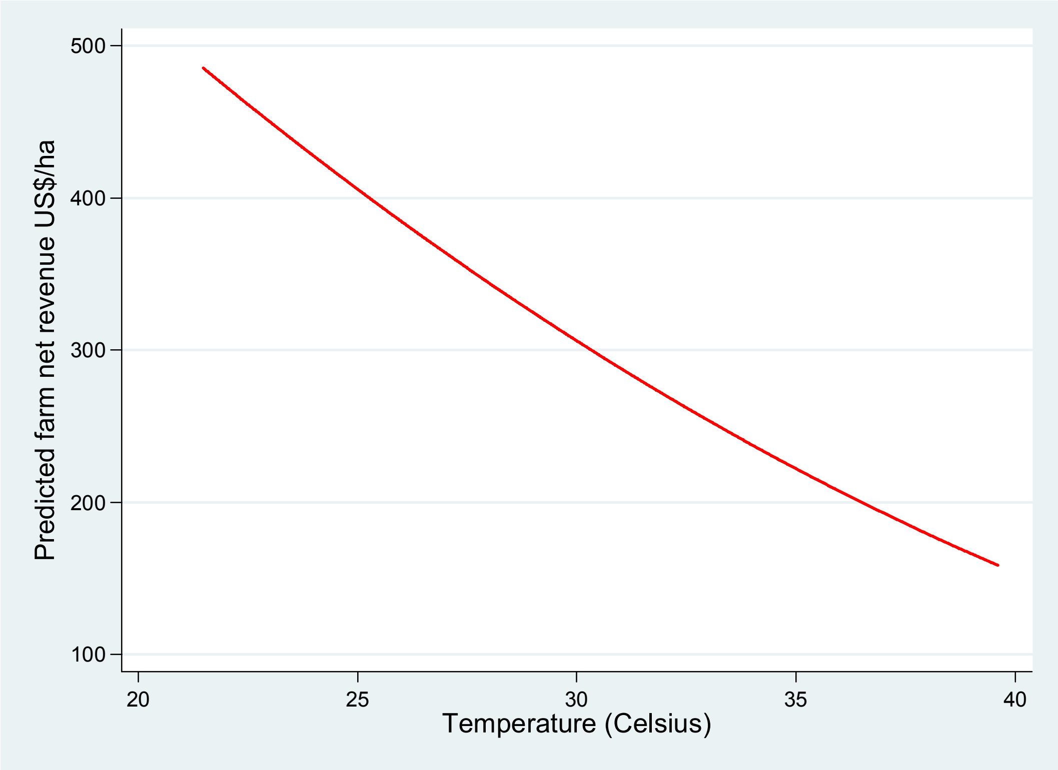


Figure 3a: Temperature response function – All farms in Africa

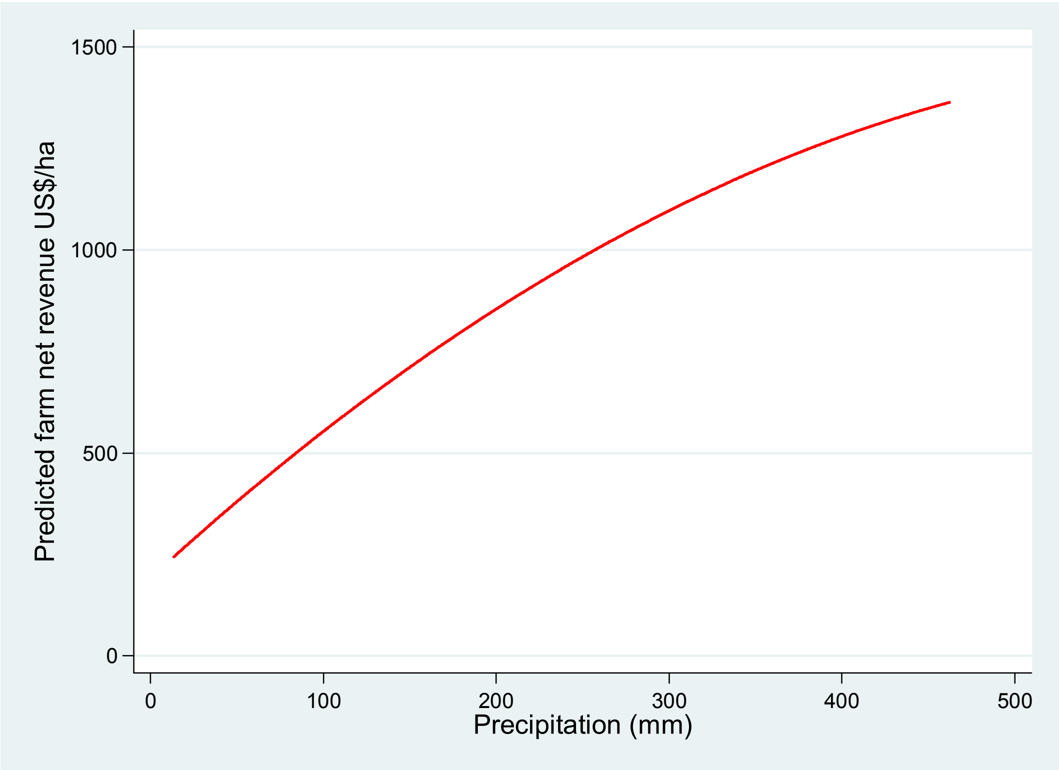


Figure 3b: Precipitation response function – All farms in Africa

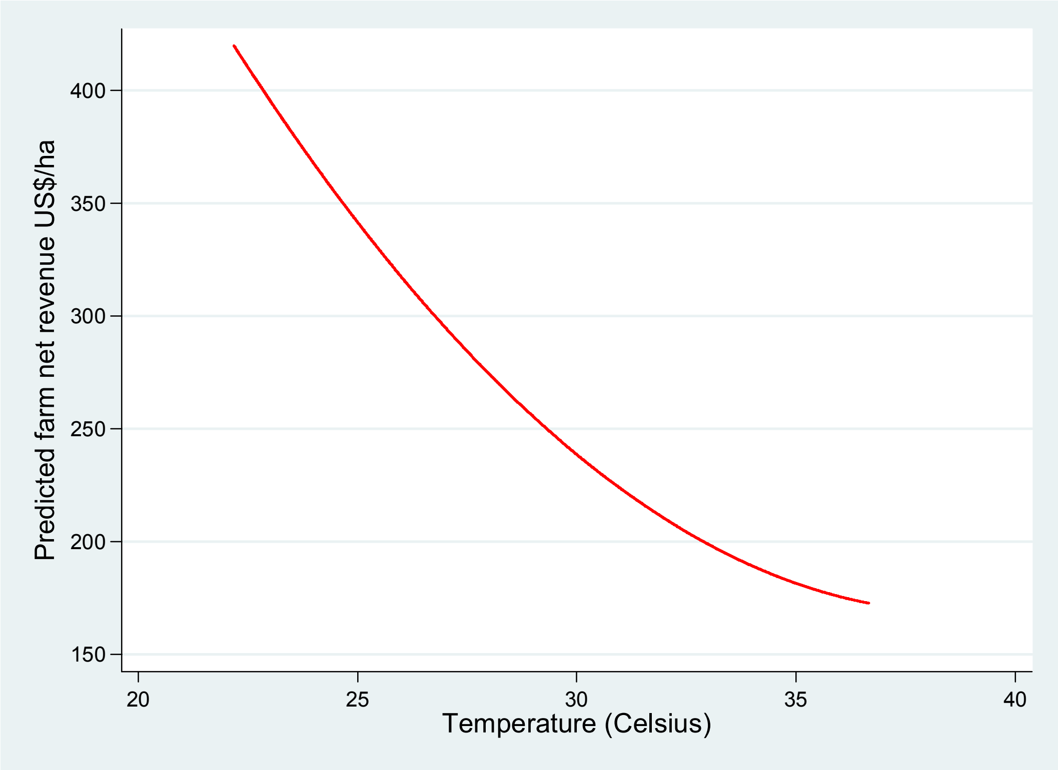


Figure 4a: Dryland farm temperature response function

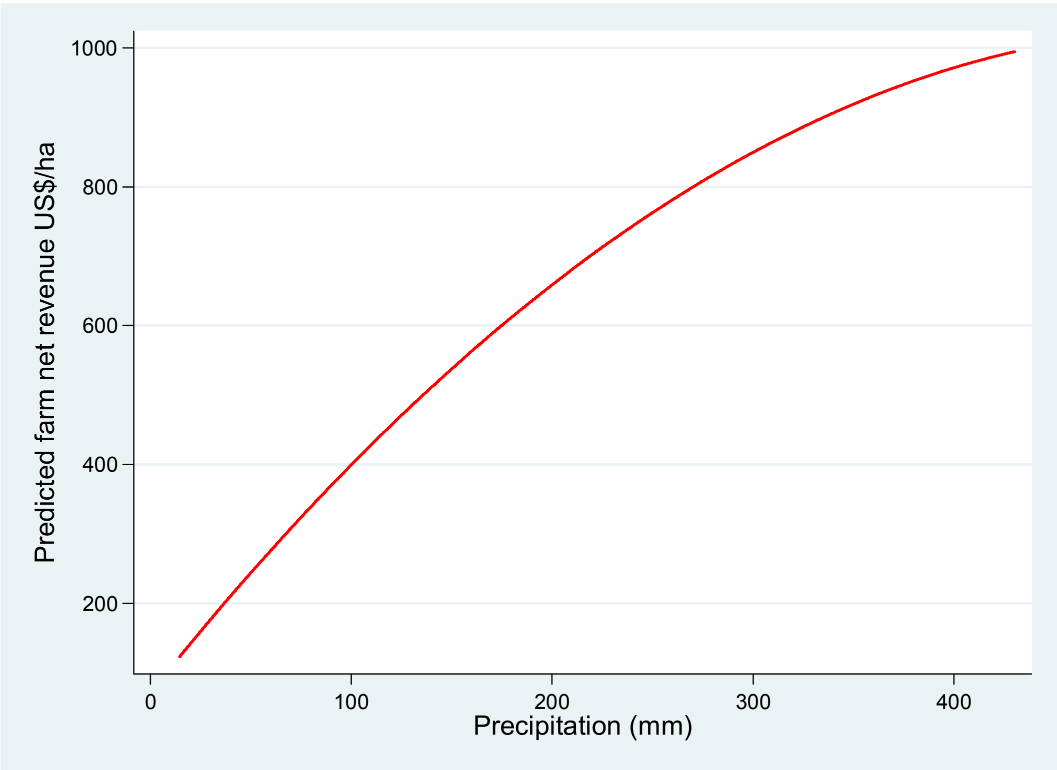


Figure 4b: Dryland farm precipitation response function

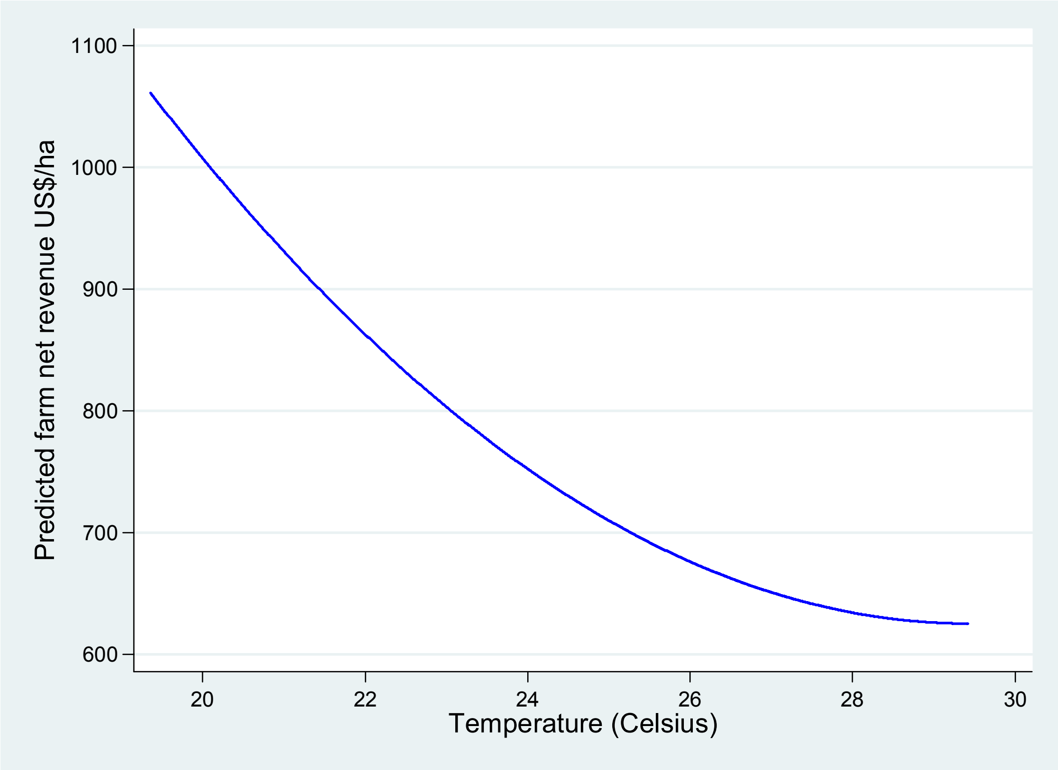


Figure 5a: Irrigated farm temperature response function

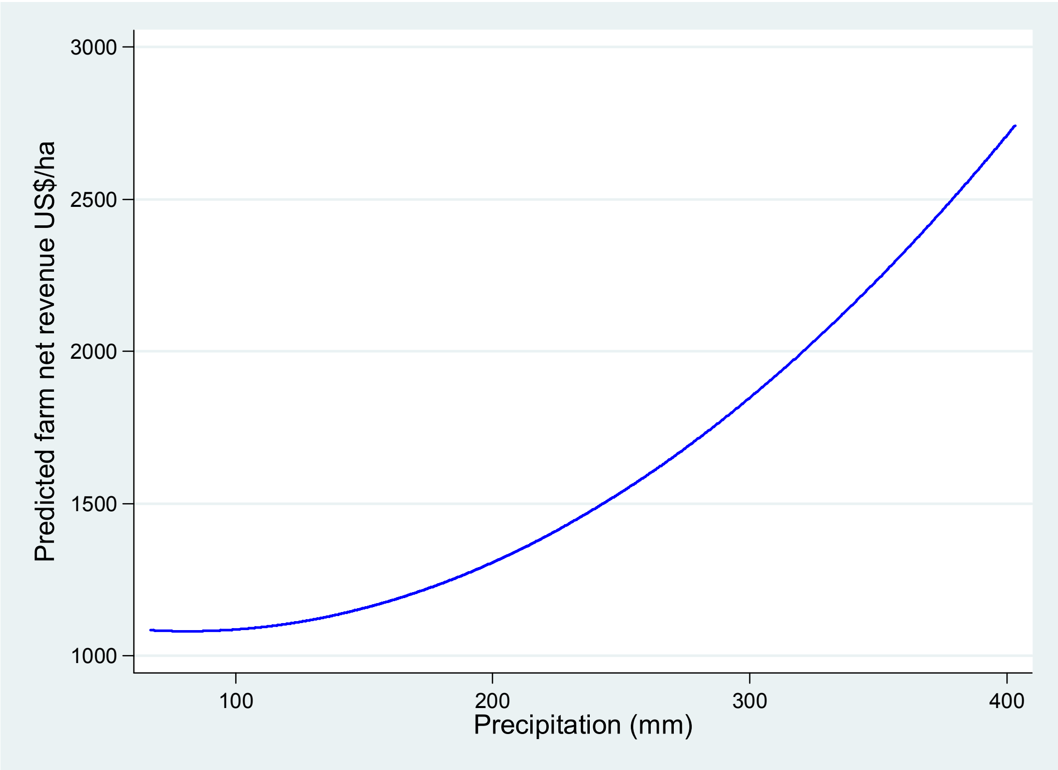
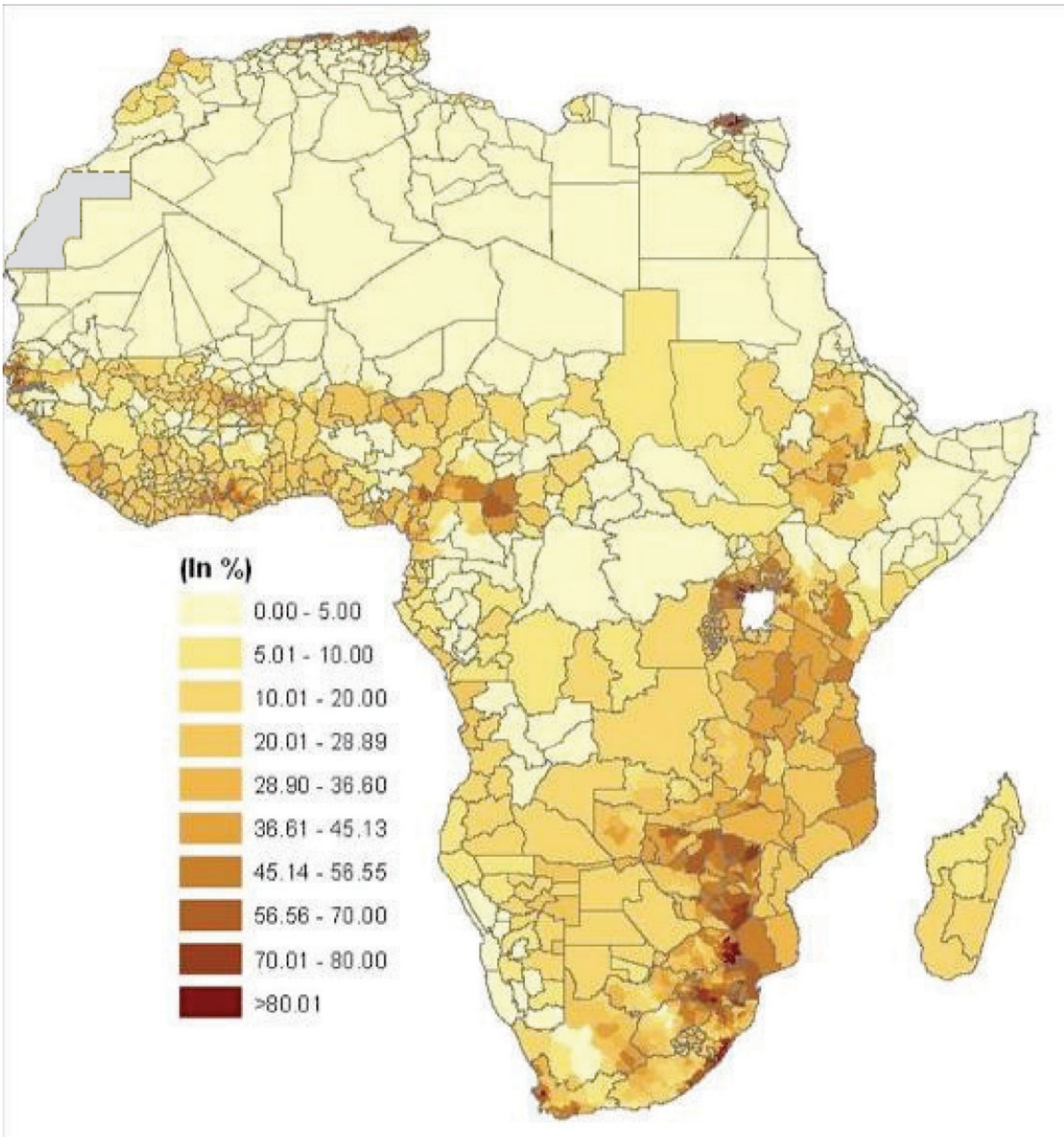
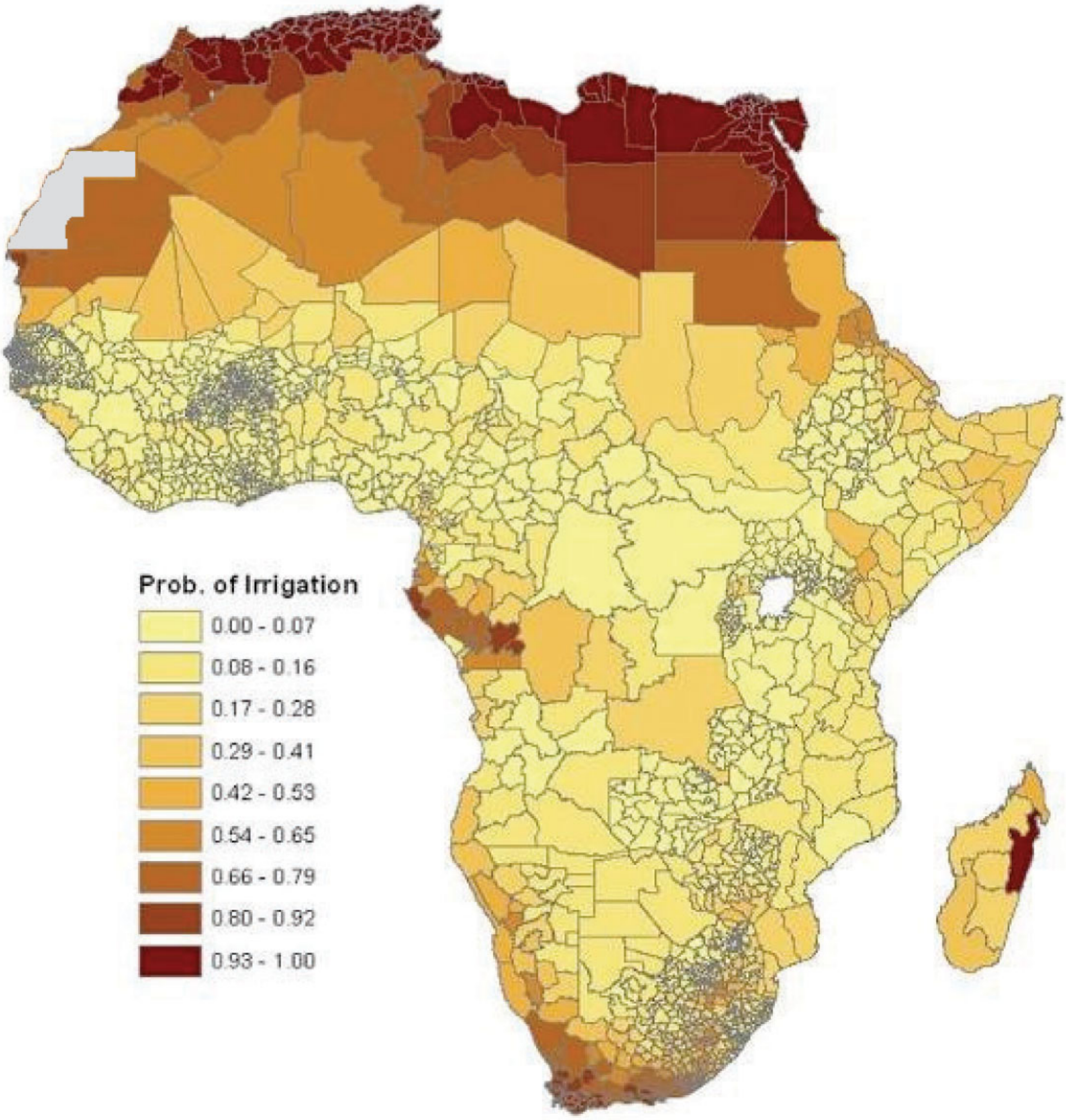


Figure 5b: Irrigated farm precipitation response function



Note: Provincial borders are shown so that the variation in percentages can be seen clearly.

Figure 6: Estimated fraction of cropland in district (Based on IFPRI data)



Note: Provincial borders are shown so that the variation in percentages can be seen clearly.

Figure 7: Estimated fraction of irrigation by location (Based on FAO data)

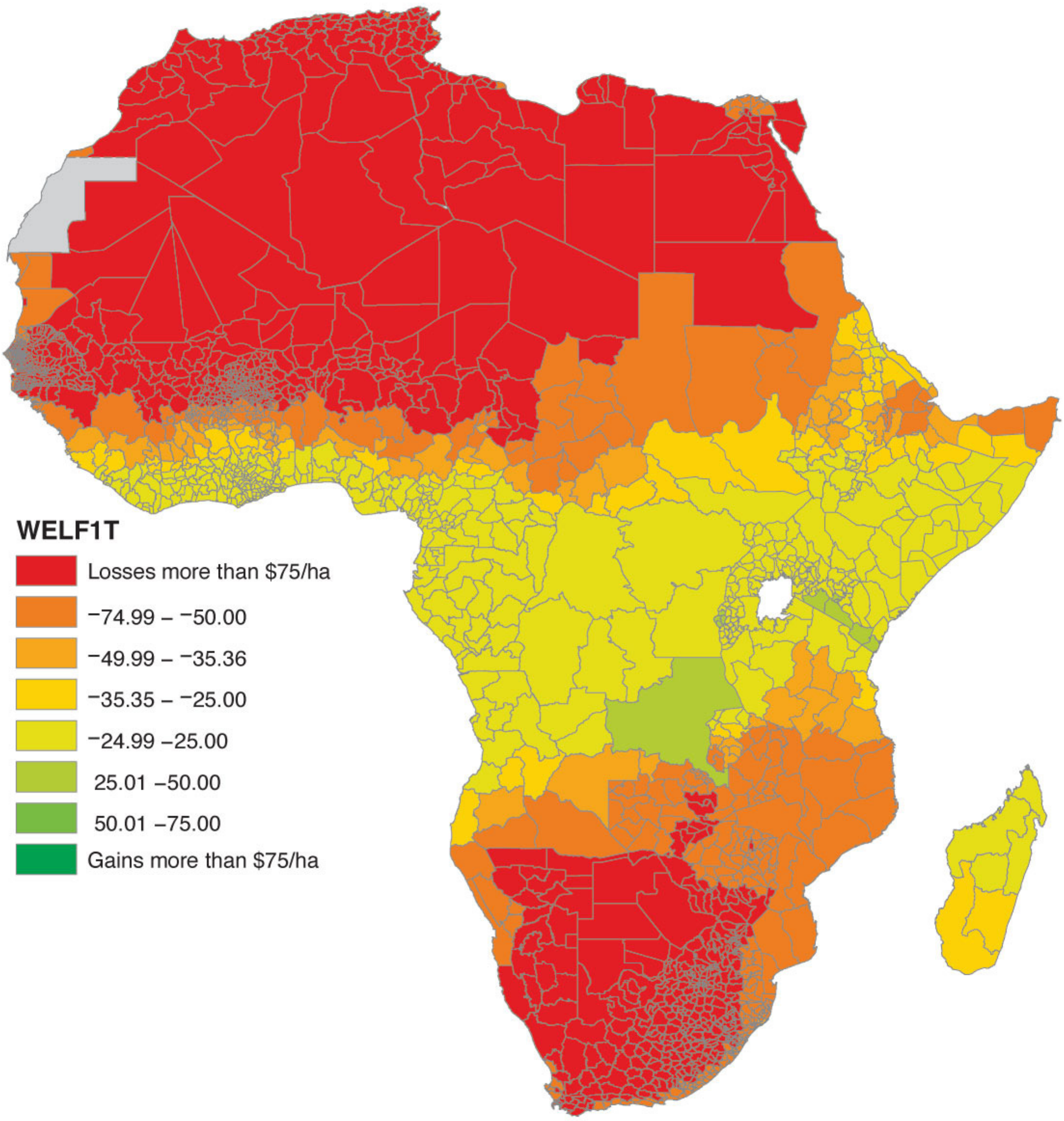


Figure 8a: Change in net revenue per hectare from 2.5°C warming

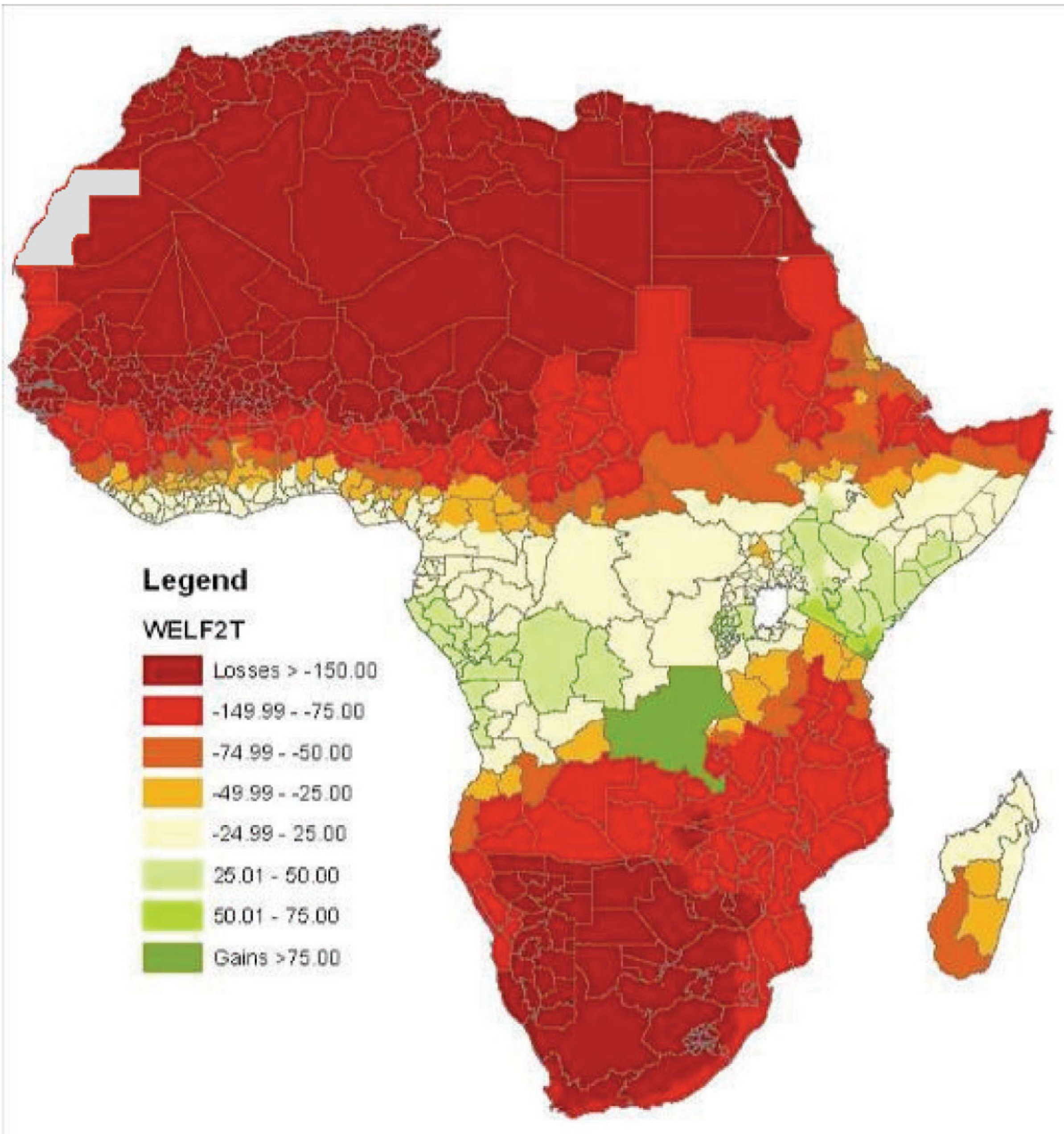


Figure 8b: Change in net revenue per hectare from 5°C warming

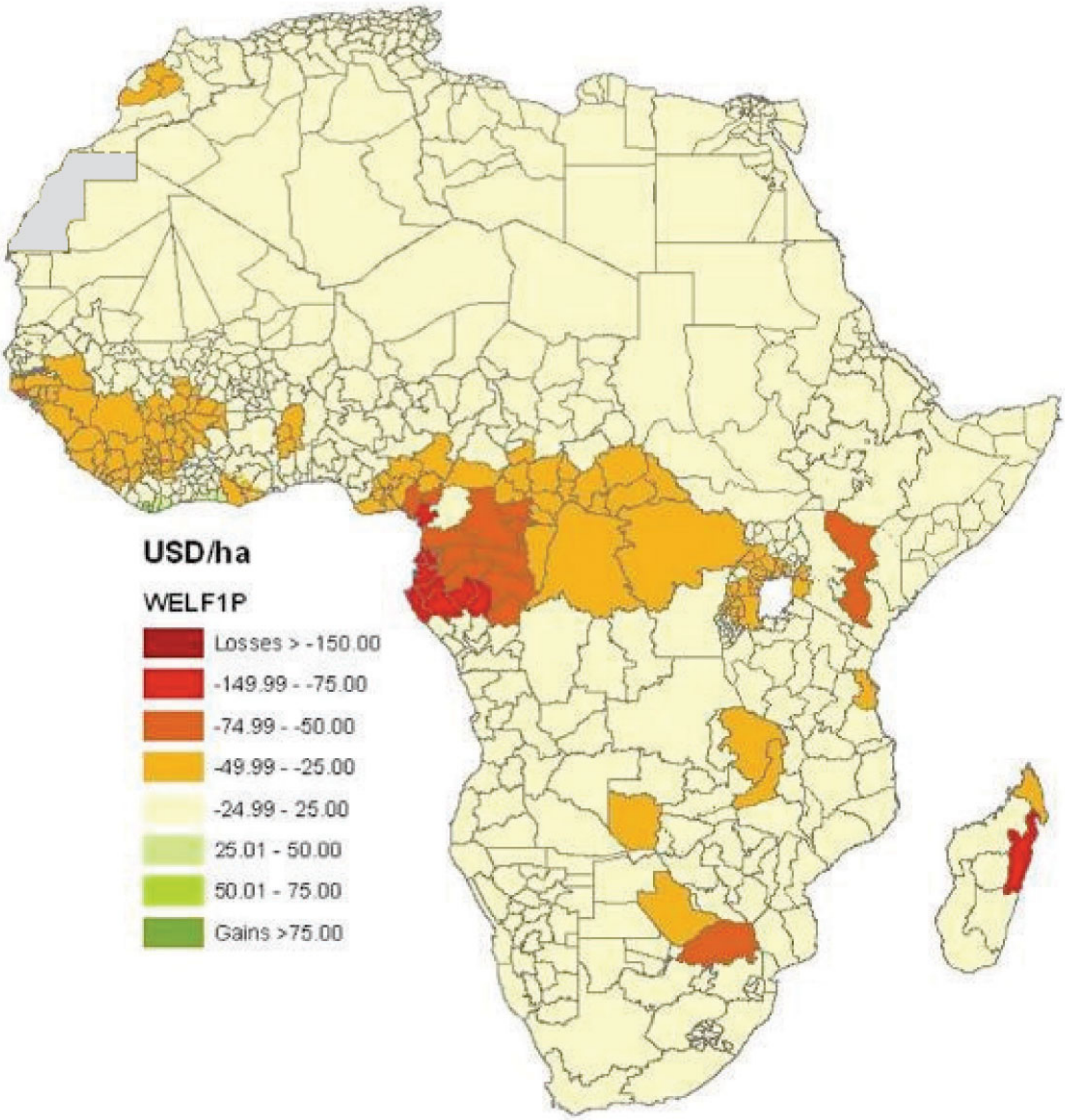


Figure 8c: Change in net revenue per hectare from 7% decrease in precipitation

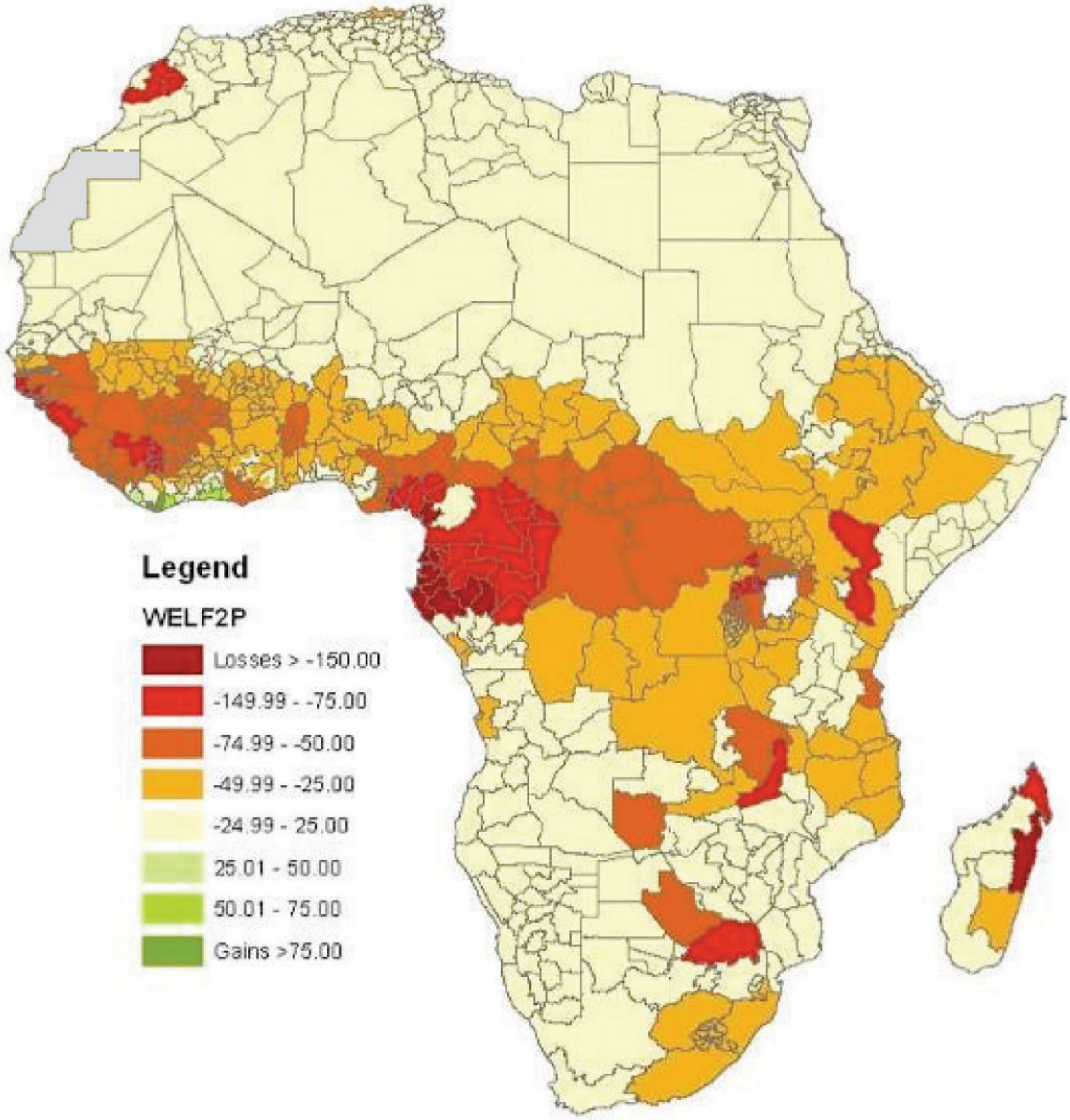


Figure 8d: Change in net revenue per hectare from 14% decrease in precipitation

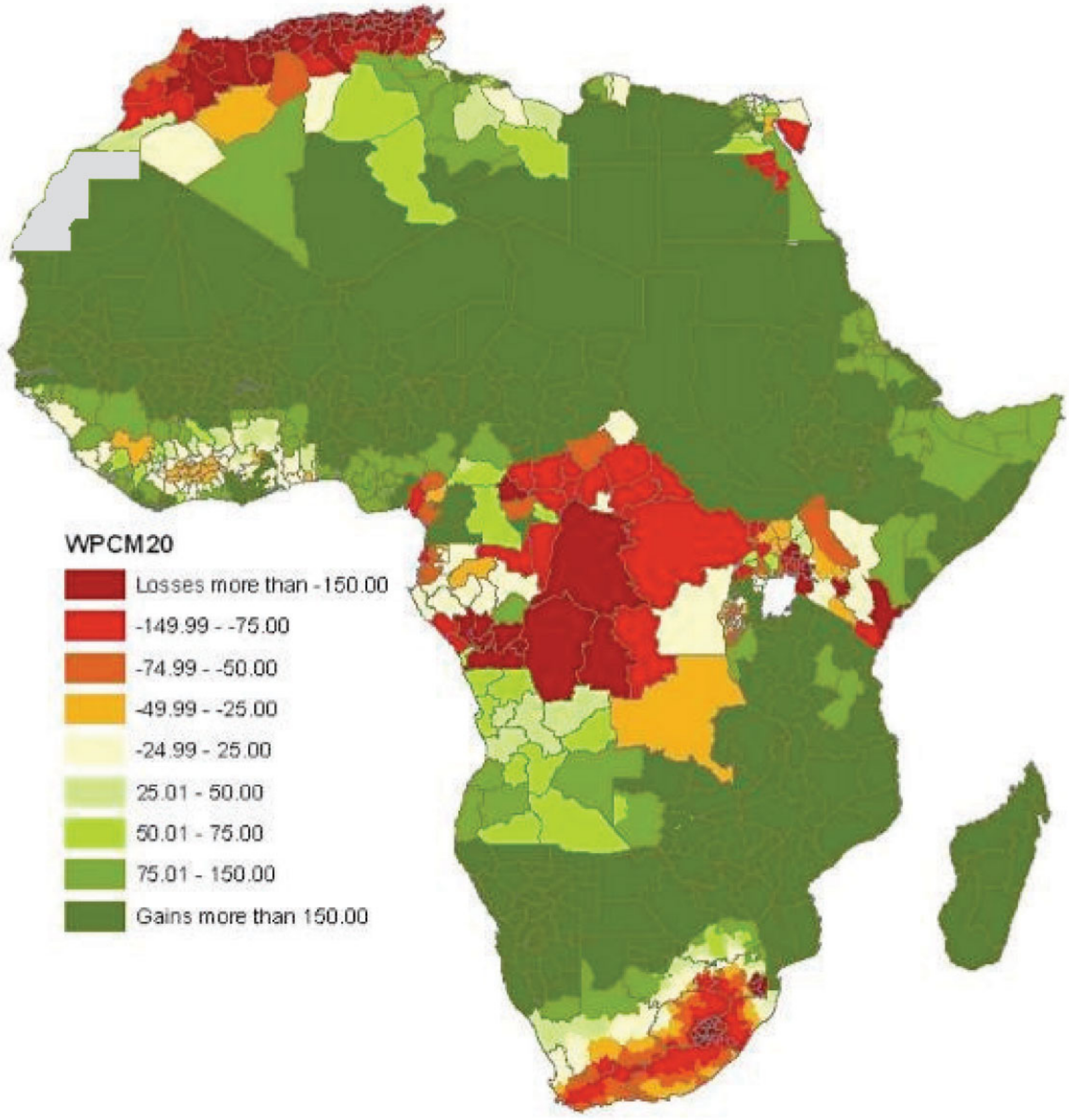


Figure 9a: Change in net revenue per hectare from PCM climate scenario in 2020

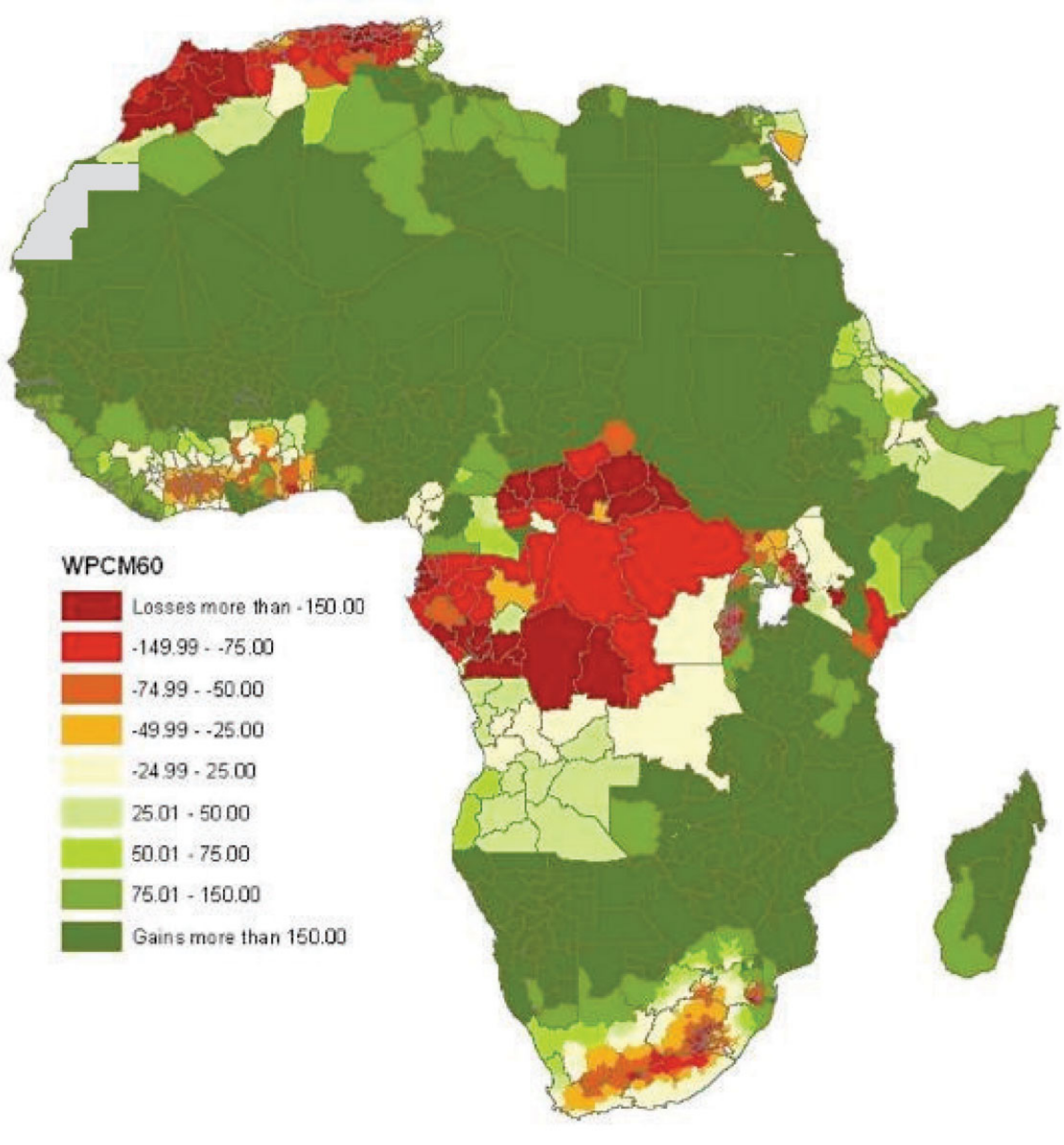


Figure 9b: Change in net revenue per hectare from PCM climate scenario in 2060

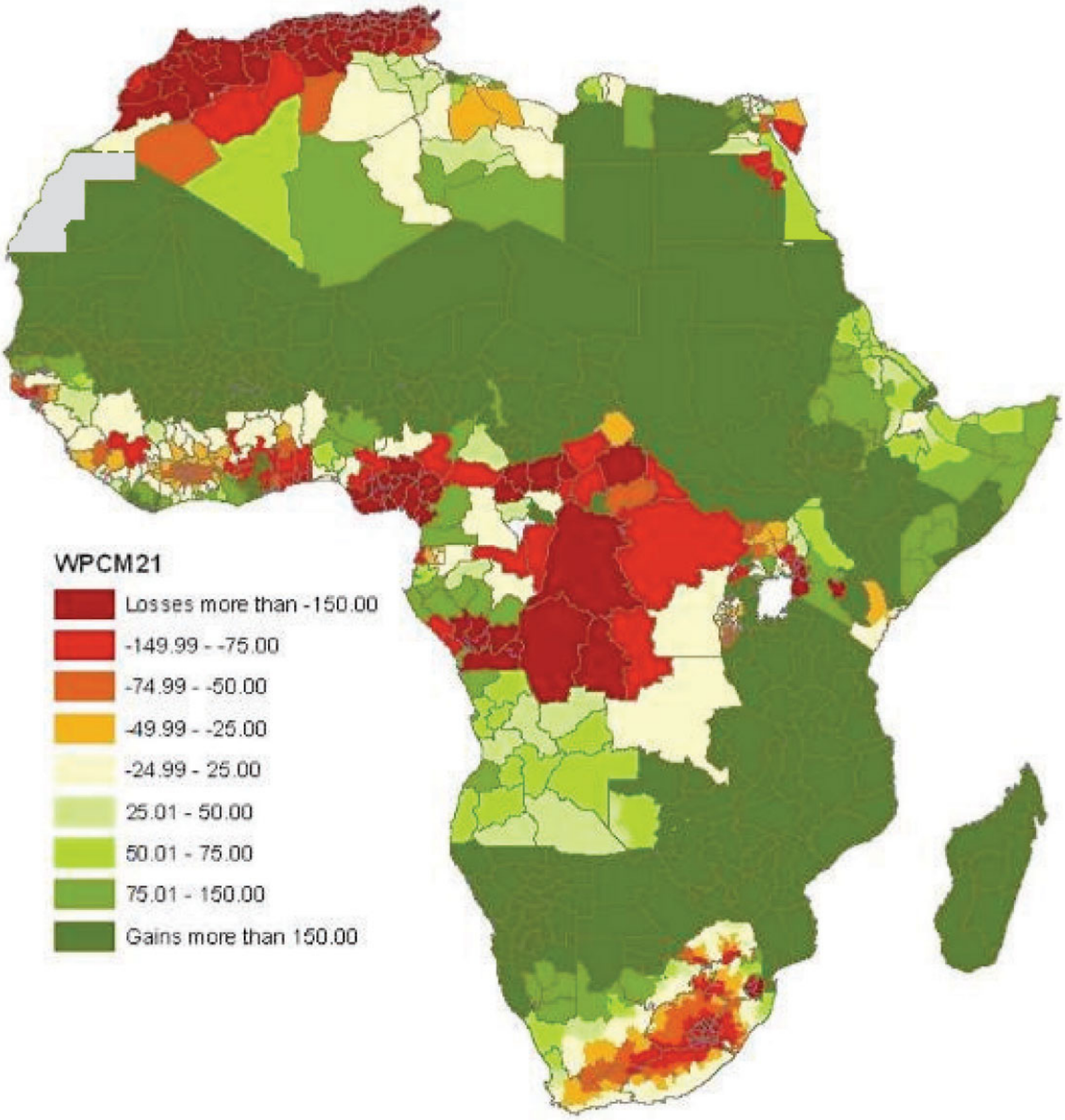


Figure 9c: Change in net revenue per hectare from PCM climate scenario in 2100

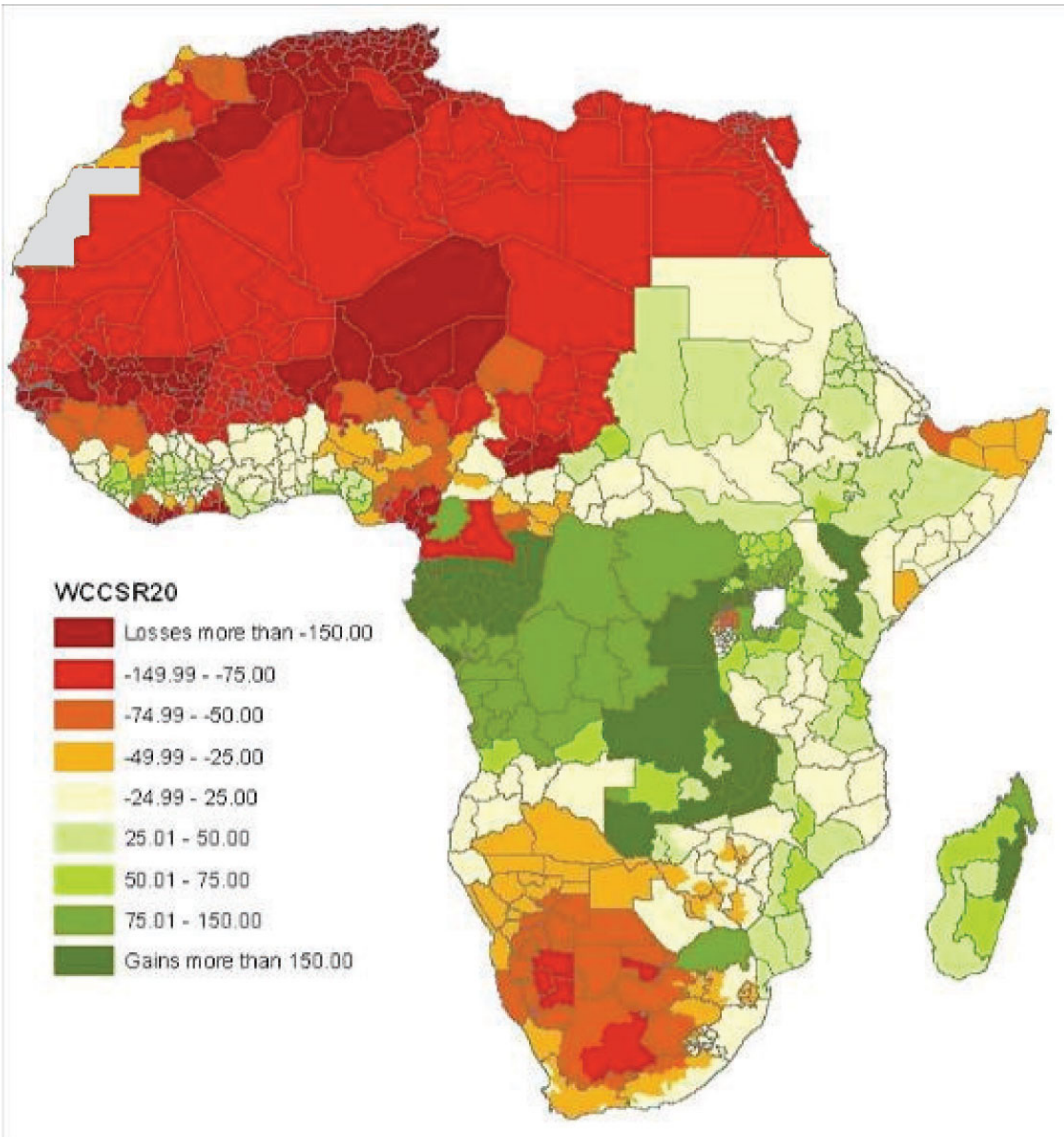


Figure 10a: Change in net revenue per hectare from CCSR climate scenario in 2020

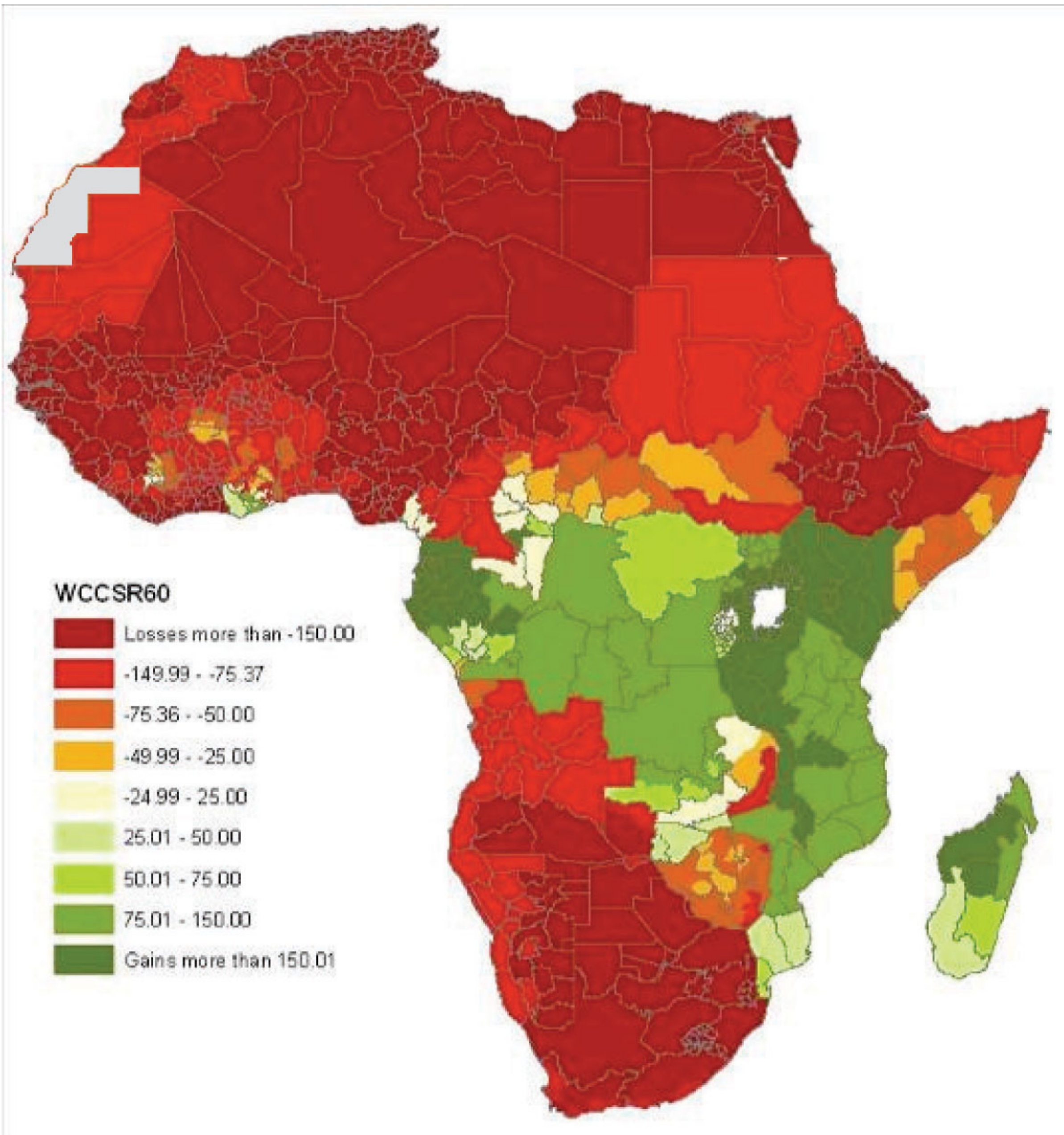


Figure 10b: Change in net revenue per hectare from CCSR climate scenario in 2060

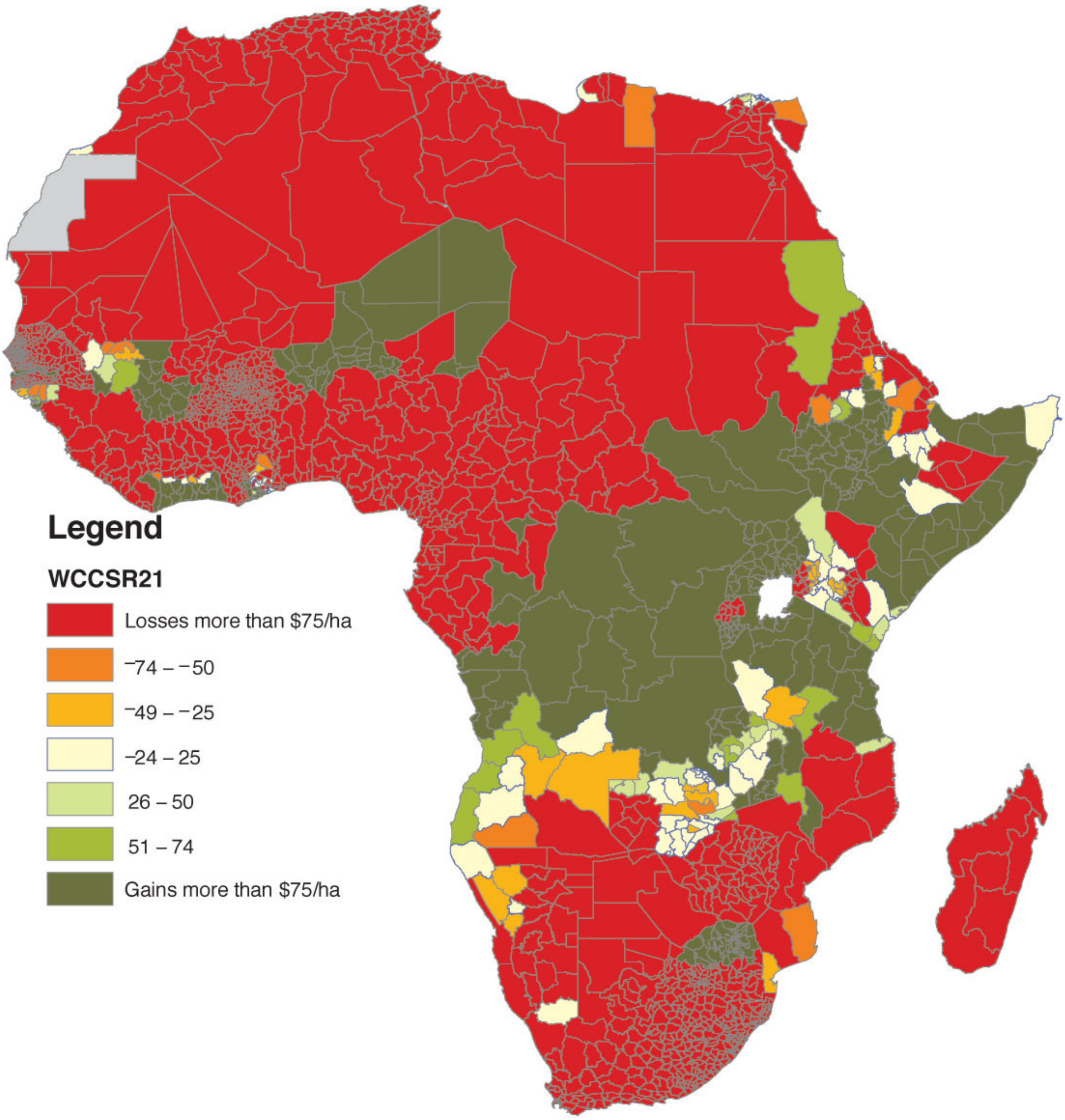


Figure 10c: Change in net revenue per hectare from CCSR climate scenario in 2100

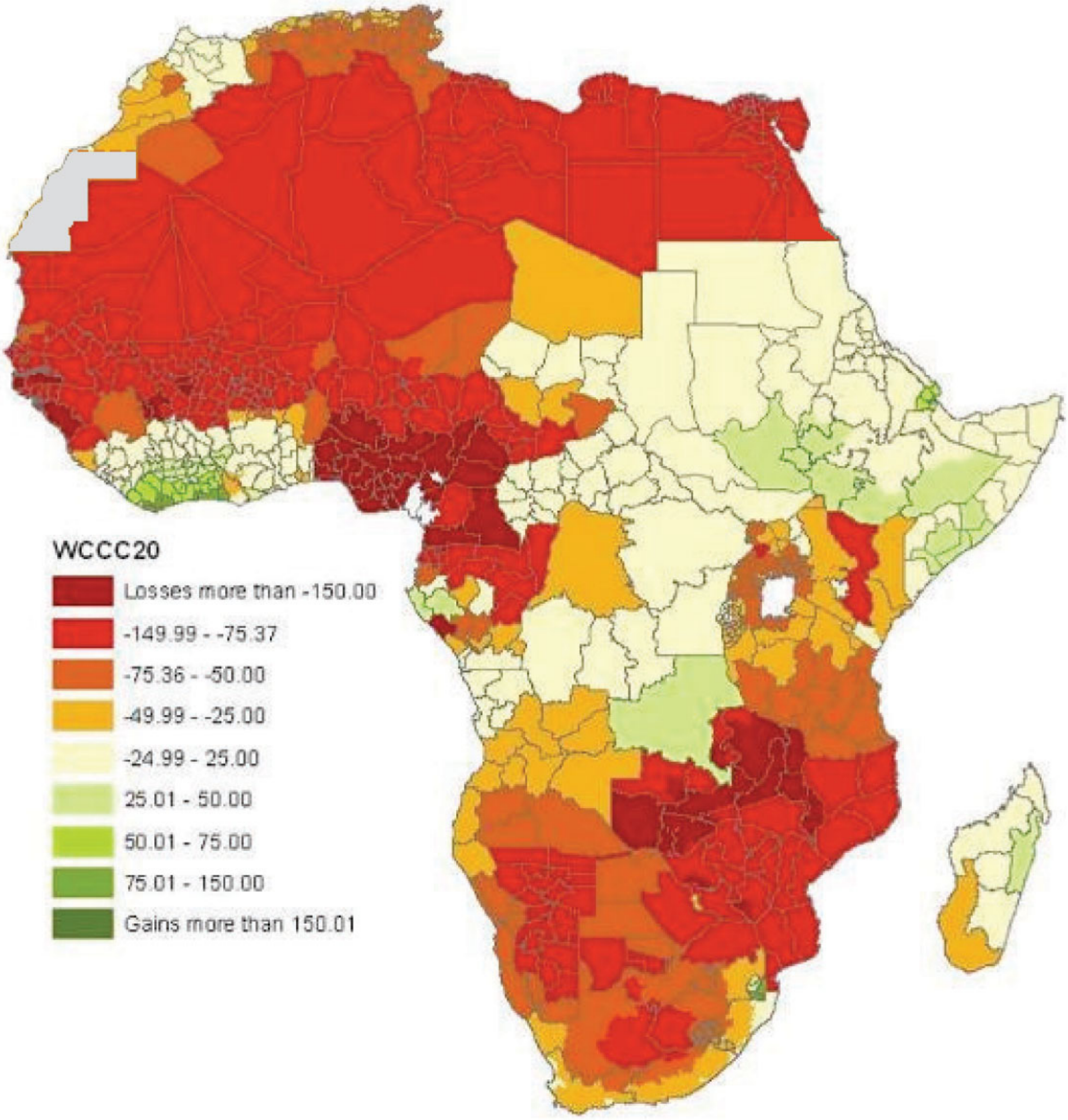


Figure 11a: Change in net revenue per hectare from CCC climate scenario in 2020

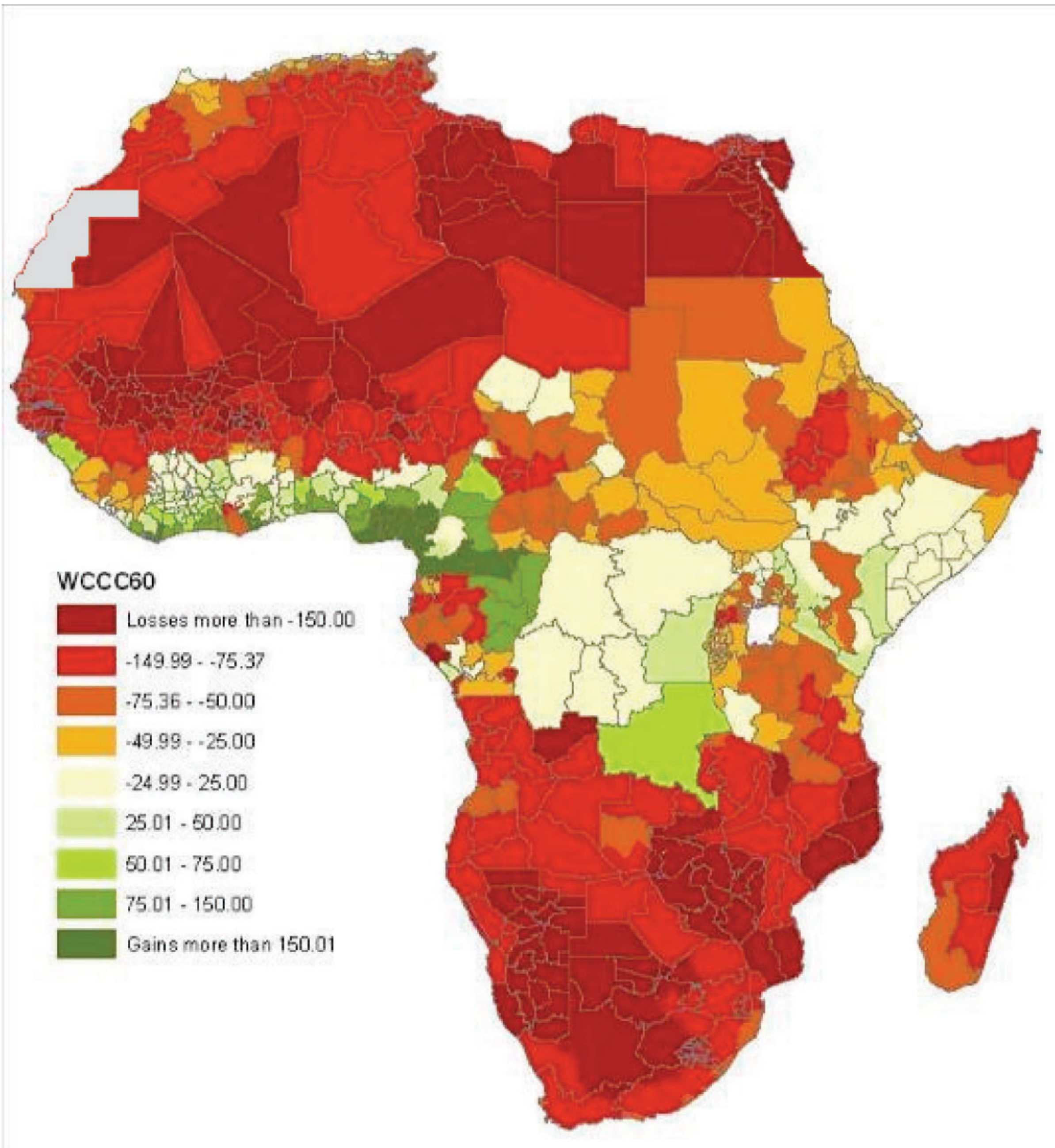


Figure 11b: Change in net revenue per hectare from CCC climate scenario in 2060

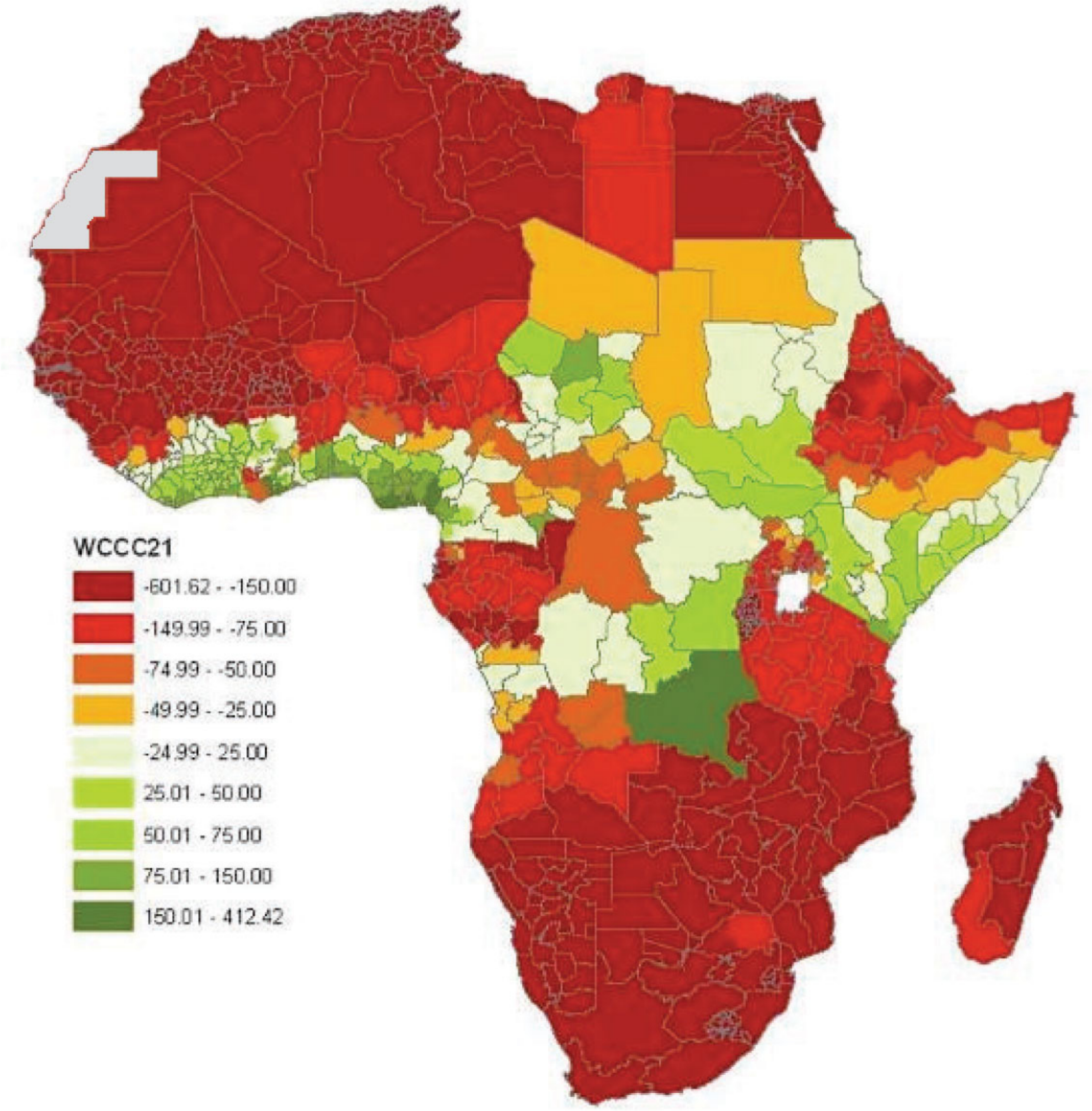
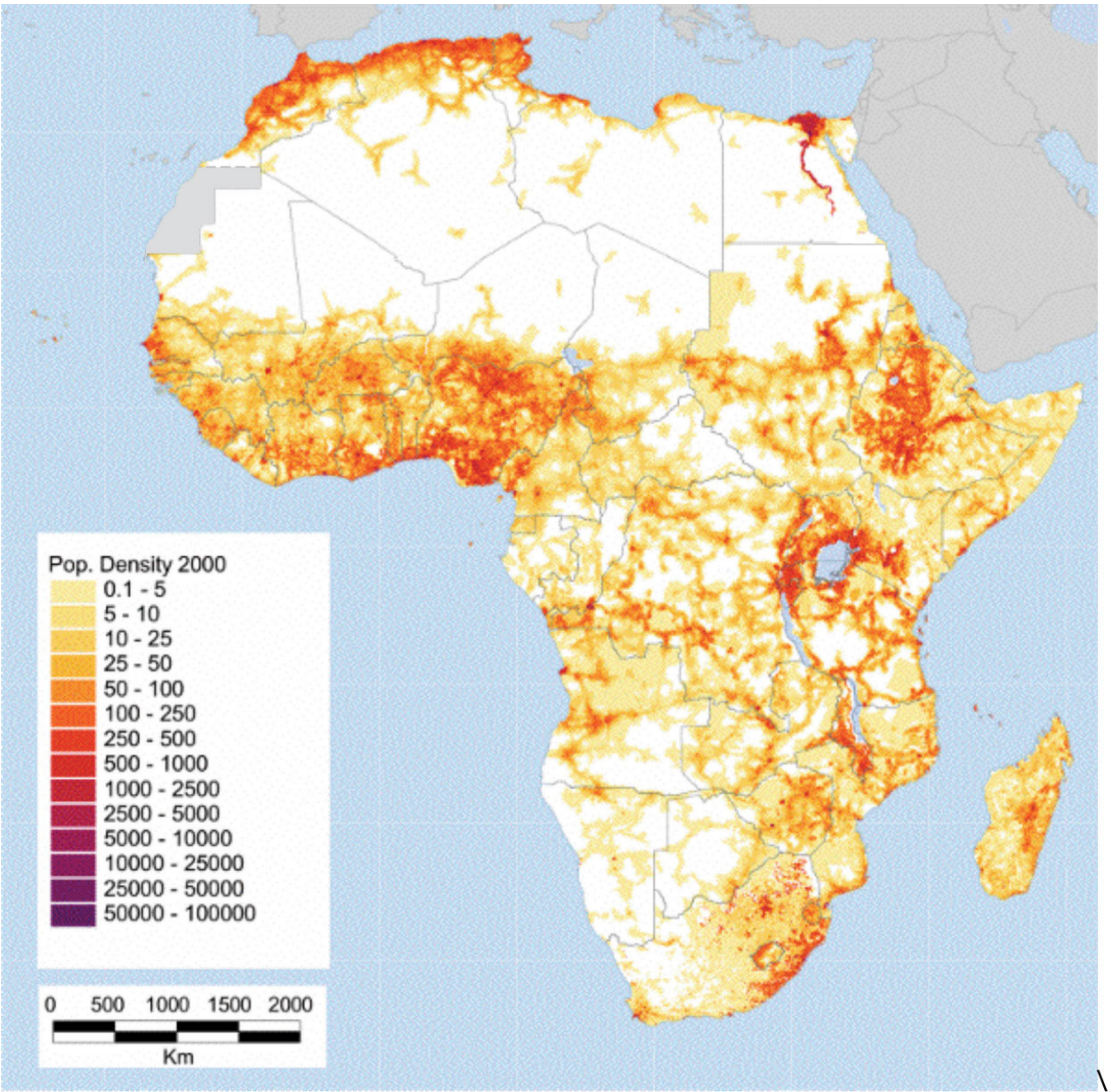


Figure 11c: Change in net revenue per hectare from CCC climate scenario in 2100



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Source: Center for International Earth Science Information Network (CIESIN)

Figure 12: Population density map (2000)